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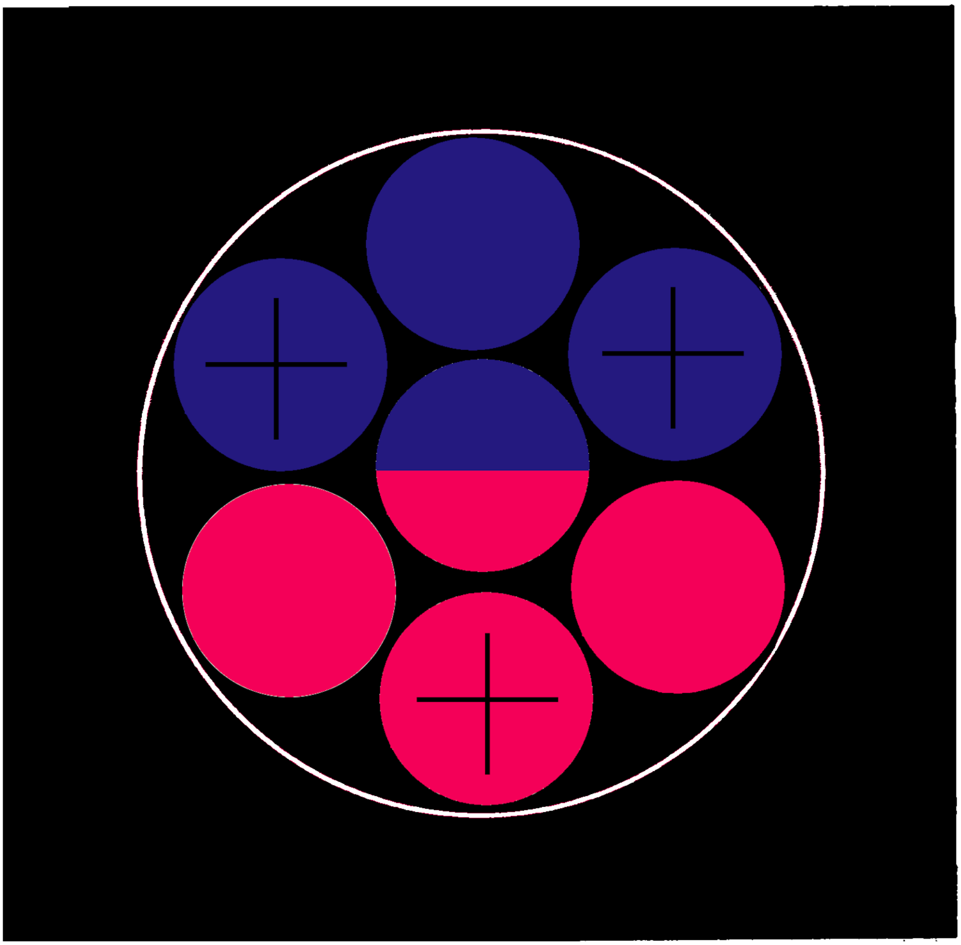
elementary particles



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Elementary Particles

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Elementary Particles

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PERGAMON PRESS

OXFORD · LONDON · EDINBURGH · PARIS · FRANKFURT

THE MACMILLAN COMPANY

NEW YORK

PERGAMON PRESS LTD.
Headington Hill Hall, Oxford
4 & 5 Fitzroy Square, London W.1

PERGAMON PRESS (SCOTLAND) LTD.
2 & 3 Teviot Place, Edinburgh 1

THE MACMILLAN COMPANY
60 Fifth Avenue, New York 11, New York

COLLIER-MACMILLAN CANADA, LTD.
132 Water Street, Galt, Ontario

GAUTHIER-VILLARS ED.
55 Quai des Grands-Augustins, Paris 6

PERGAMON PRESS G.m.b.H.
Kaiserstrasse 75, Frankfurt am Main

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This translation has been made especially for inclusion in this Library from A. A. Sokolov's book entitled *Elementarnye Chastitsy*, published in Moscow, 1963, by Izdatel'stvo Moskovskogo Universiteta

Library of Congress Catalog Card No. 64–20742

Set in 10 on 12pt. Times and Printed in Great Britain by
THE WHITEFRIARS PRESS LTD., LONDON & TONBRIDGE

*Contents**

* *This is the extended text of a public lecture delivered at Moscow State University on 10 January 1962.*

1

Introduction

THE development of modern physics proceeds under the flag of atomic theory. It is well known that the smallest particle of a chemical element is called an atom, which, translated from the Greek means "indivisible". The most recent investigations have revealed the complexity of the atom, which consists of even smaller so-called elementary particles. Originally the term "elementary particle" (just as for the term "atom" at that time) included the concept of indivisibility. However, scientists nowadays have studied more closely the structure of the elementary particles and consequently this indivisibility must nowadays be accepted with a certain amount of arbitrariness.

In studying the atom, the principal role is played by four elementary particles: the proton (p), neutron (n), electron (e) and the photon (γ). According to the theory of Ivanenko and Heisenberg, protons and neutrons comprise the nucleus, which represents the densest part of the atom (Fig. 1).

Electrons rotate around the nucleus; they are retained in the atom as a result of the Coulomb attraction acting towards the nucleus (Rutherford's planetary model of the atom).

Photons are formed in the atom as a result of transition of electrons from a higher energy level to a lower one. As a result of the reverse transition, absorption of photons by the atom occurs.

We shall consider first of all these four elementary particles.

Their principal characteristics are rest mass, charge and spin. The latter describes, as it were, the rotation of the particles, i.e., their internal properties.

In atomic physics, the units chosen for rest mass and charge are the rest mass of the electron $m_0 = 0{\cdot}9 \times 10^{-27}$ g, and the elementary charge $e_0 = 4{\cdot}8 \times 10^{-10}$ e.s.u. Spin is measured, as is well known, in units of $\hbar$.

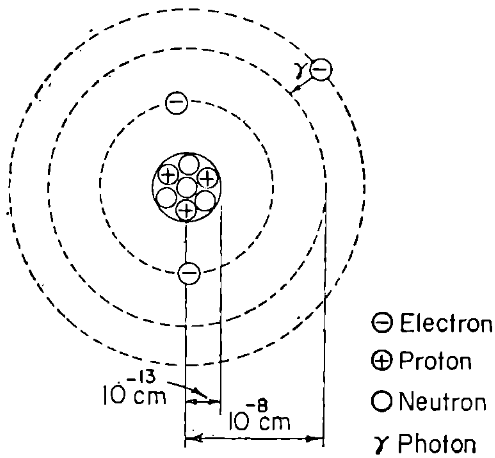

FIG. 1. *Planetary model of the atom.*

Then,

for the electron	$m_e = m_0$;	$e_e = -e_0$;	$s_e = \frac{1}{2}$;
for the proton	$m_p = 1836\ m_0$;	$e_p = e_0$;	$s_p = \frac{1}{2}$;
for the neutron	$m_n = 1838{\cdot}6\ m_0$;	$e_n = 0$;	$s_n = \frac{1}{2}$.

Since the electron is a charged particle, the presence of the spin (s) (i.e., the intrinsic angular momentum) leads to the phenomenon of the magnetic moment of the electron, the component of which in the direction of the spin has a negative sign, since

$$e_e = -e_0 < 0$$

$$\mu_e = -\mu_0 = -\frac{e_0}{2m_0 c}\hbar$$

where μ_0 is the Bohr magneton and Planck's constant

$$h = 2\pi\hbar = 6{\cdot}62 \times 10^{-27} \text{ erg sec}$$

The proton and the neutron also possess a magnetic moment, but more will be said of this below.

We shall now say something about the photon. It was thought at one time that light is a train of electromagnetic waves and that electrons are corpuscles, i.e., particles.

It was then discovered that light also possessed corpuscular properties (according to Einstein's photon theory, the energy of the light quantum of frequency ν is $\varepsilon = h\nu$), which are manifested, for example, in the emission of photons, and that electrons possessed wave character (De Broglie waves, $\lambda = h/m_0 v$), which can be detected, in particular, by passing a beam of electrons with velocity v through a crystal (electron diffraction). Nowadays there is a well-developed branch of science, called *electron optics*, upon which are based the calculations for the construction of electron microscopes.

Photons differ from electrons primarily in the absence of rest mass ($m_\gamma = 0$) and in the value of the spin (the spin of the photon is equal to unity).

We shall dwell below on the prediction and discovery of new elementary particles.

2

Prediction of the Positron by Dirac and its Experimental Discovery

IT IS well known that Dirac developed a wave equation which takes into account not only relativistic but also spin effects.

The discovery made by Dirac is of the same extreme importance for science as the discovery of the three basic laws of mechanics and the law of universal gravitation by Newton, Maxwell's basic equations for the electromagnetic field or Einstein's Theory of Relativity.

Bohr's semi-classical theory and even Schrödinger's wave equation were only preliminary theories which can be considered as some intermediate stage *en route* to the theory established by Dirac.

Dirac, by means of the wave equation, first succeeded in giving the correct explanation of the fine structure of the spectral lines of hydrogen-like atoms, and also to postulate the theory of splitting of the lines in the emission spectrum of atoms placed in a magnetic field (the anomalous and normal Zeeman effect).

At the same time, it can be shown that at first sight Dirac's theory leads to difficulties, associated with the interpretation of negative energies, which would appear to be non-removable. A more detailed analysis of them, however, led to a new funda-

mental discovery, which underlies the whole of the modern theory of elementary particles.

Actually, in relativistic mechanics, the energy E of a free particle is related to its momentum p and its rest mass m_0 by the relationship

$$E^2 = c^2 p^2 + m_0^2 c^4$$

where c is the velocity of light. This relation permits two equivalent solutions:

$$E = \pm |E|, \qquad |E| = \sqrt{c^2 p^2 + m_0^2 c^4}$$

one of which corresponds to a positive energy and the other to a negative energy. A state with negative energy can be shown to be

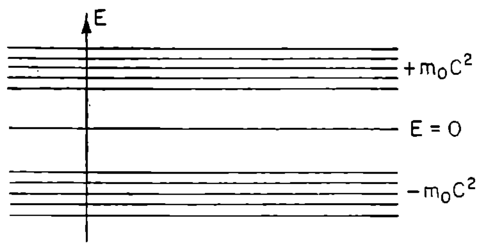

FIG. 2. *Diagram of the possible energy levels of the free Dirac particle.*

unreal, since the region of negative energies is extended to infinity ($E \to -\infty$), and thus no stable minimum energy state could exist (Fig. 2).

In classical physics, the energy of a particle, as a result of its motion, can be changed only continuously and therefore a transition from a state with a positive energy ($E > m_0 c^2$) to a state with negative energy ($E < -m_0 c^2$) is completely inadmissible, since then the energy is changed discontinuously ($\Delta E \geqslant 2m_0 c^2$). Thus, having excluded at the initial instant of time states with a negative energy, we need not at all introduce them at a later time, i.e., there are no difficulties with negative energy states.

We have a completely different state of affairs in quantum theory, where transitions with discrete energy changes are quite permissible. Then the state with a negative energy cannot be

mechanically eliminated, since the probability of transition between energy levels of $+m_0 c^2$ and $-m_0 c^2$ will differ from zero.

After the appearance of Dirac's relativistic theory (1928) nobody drew attention to this difficulty at first. The majority of authors suggested that the state with negative energy, just as in classical theory, should be simply rejected. Since this rejection in the quantum theory was mathematically strictly without any foundation, the presence of a state with negative energy was known by the name of the "plus–minus difficulty".

For a number of years this problem remained open, and only in 1931 did Dirac find an extremely original solution to it. He suggested that all states with a negative energy are filled with electrons. Therefore, in accordance with Pauli's principle, according to which there can be only one electron in every quantum state, electrons with positive energy cannot pass into these occupied states.

According to Dirac, empty space should actually be a "sea" of electrons (vacuum), which completely fill the states with negative energy, and at the same time all states with positive energy remain free (Fig. 3).

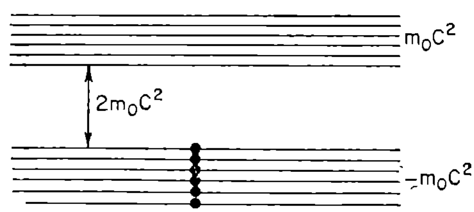

FIG. 3. *Diagram of the ground state of the electron–positron vacuum.*

Let us now assume that a gamma-quantum with energy greater than $2m_0 c^2$, acting on an electron in the vacuum, transfers it to a state of positive energy (Fig. 4).

In this case, in place of the absorbed gamma-quantum an electron appears with positive energy and simultaneously a "hole" in the background of the "sea" of electrons with negative energy,

having a negative inertial mass

$$m = -\frac{|E|}{c^2} < 0$$

Since the acceleration of the particle is equal to the ratio of force to mass, then particles with negative mass will move in the opposite direction of the action of the force.

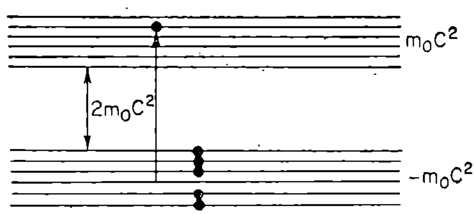

FIG. 4. *Diagram of the formation of electron–positron pairs.*

As regards the "holes", their motion should recall the movement of a bubble in the sea. It is well known that bubbles in the sea under the action of gravity will move upwards, i.e., contrary to the motion of the water itself. If the water possessed negative mass, then under the action of the force of gravity (if the gravitational mass remains positive as a result of this) it should move upwards, consequently bubbles in the sea should fall to the ground as particles with positive mass.

The zero charge of the vacuum (i.e., the states with negative energy) is somewhat increased as a result of the appearance of a "hole", since in this case there is missing from the vacuum a single electron which is negatively charged. Consequently, the "hole" in the background of the "sea" of electrons with negative energy will not only behave as a particle with positive mass, equal to the mass of the electron, but also as a particle with positive charge. This particle has been named the positron.

Modern theory also permits the reverse process, namely, as a result of the presence of a positron (i.e., "holes" in the background of negative levels), an electron with a positive energy can transfer

to this "hole", emitting as a result of this a gamma-ray, the frequency of which can be found from the Law of Conservation of Energy (Fig. 4).

Entirely as Dirac predicted, the positron was discovered by Anderson at the end of 1932. The conversion of an electron and a positron into a gamma-quantum was demonstrated experimentally. This process was called annihilation. In fact, as a result of this, it is not destruction of the particles which occurs, but their transformation into other particles.

From that instant, a new era of development of the theory of elementary particles commenced, taking into account the possibility of their mutual conversions.

With many of the foremost discoveries, legendary stories are frequently associated with how they happened. For example, there is the well-known legend that Newton's Law of Universal Gravitation was discovered supposedly by analysing the fall to earth of an apple.

In Cambridge (England), a popular legend was that Dirac interpreted the "holes" in a background of negative energy as positrons as a result of a dream. Dirac willingly participated in competitive problems organised by the Cambridge Students Mathematical Union. One of these problems was the following. Three fishermen caught a haul of fish and lay down on the shore to sleep. One of the fishermen awoke and decided to leave, taking his share of the catch. He discovered that he could divide the catch into three if he threw one fish into the sea. This he did, and taking his third share, he went home. Soon the second fisherman woke up, who, not suspecting that the first one had gone, again began to divide the catch. Just like the first fisherman, he divided the whole catch into three parts and also discovered that one fish remained over. Having thrown it away he took his third share of the catch and went home. The third fisherman went through exactly the same operation, discovering that as a result of dividing up the catch into three parts there was again one fish left over. It was required to determine how many fish there were

originally, indicating as a result of this the minimum permissible number.

If the calculation is carried out by a trivial method, then an answer is obtained of twenty-five fish. However, Dirac suggested another answer, viz., minus two (-2). Indeed, if one fish is thrown away, then minus three fish remain, which can be divided into three and for the next fisherman once again there remain minus two fish and so on.

As the legend says, further reflections by Dirac on this answer made it appear as a completely paradoxical result and led him to the greatest discovery of modern times.

It should be noted that an electron and a positron can also form an atom-like system of the hydrogen atom type, in which a proton is replaced by a positron. This combination was given the name positronium. The lifetime of the positronium atom depends strongly on the value of the total spin of the system, since as a result of annihilation, i.e., by the mutual transformation of the particles, the Laws of Conservation of Momentum and Spin should be maintained. Parapositronium (the spins of the electron and positron are antiparallel) can be converted into two gamma-quanta, which should fly off in opposite directions with oppositely-directed spins (the total momentum and total spin of the gamma-quanta will also be equal to zero). The lifetime of parapositronium is equal to $1{\cdot}25 \times 10^{-10}$ sec.

The spin of orthopositronium is equal to unity. Neither it nor parapositronium can decay into a single gamma-quantum, since in this case the Law of Conservation of Momentum will be violated. As a result of decay of orthopositronium into two gamma-quanta, the Law of Conservation of Spin will not be fulfilled, since for two gamma-quanta it is equal to either two or zero. Only by decay into three gamma-quanta can the Laws of Conservation of Momentum and Spin be simultaneously satisfied. Therefore the probability of decay of an orthopositronium is strongly reduced, and its lifetime is increased to $1{\cdot}4 \times 10^{-7}$ sec. Ortho and parapositronium have already been discovered experi-

mentally and are finding considerable application in investigations in many regions of physics, including even condensed media.

It should be noted that the modern theory of the vacuum is far more complex than its initial version as proposed by Dirac.

For example, the whole theory should by symmetrical relative to the substitution of electrons by positrons. Therefore, having made the calculation (arising from the assumption that the electron is a particle and the positron is a "hole"), we should repeat it, assuming now that the positron is the particle and the electron is the "hole". Then the true result should be equal to the arithmetic mean of these two results. In particular, it follows that the charge of the vacuum is reduced to zero.

The theory of the electron–positron vacuum enabled calculations to be made on the conversion of a gamma-quantum into a pair of an electron and a positron and vice versa. In order that the Laws of Conservation of Momentum and Energy should be strictly maintained in the reverse transformation, the number of gamma-quanta should be not less than two.

Pair formation takes place, as a rule, by the absorption of a gamma-quantum by the nucleus, which also takes part of the momentum.

Moreover, the theory of the electron–positron vacuum enabled a new approach to be made towards the question of the structure of the elementary particles. It is well known that Lorentz already pointed out the close connection of the electron with the electromagnetic field produced by it. More precisely, he postulated that the entire mass of the electron is determined by the energy U of this electromagnetic field:

$$m^{\mathrm{el}} = \frac{U}{c^2} = \frac{be_0^2}{c^2 r_0}$$

where c is the velocity of light and b is a coefficient of order unity, depending on the charge distribution within the electron, represented by its spherical radius r_0.

In using the theory of the electromagnetic mass, according to

Lorentz, the following law governing its variation with velocity was stated for the first time:

$$m^{\mathrm{el}} = m_0 \Big/ \sqrt{1 - \frac{v^2}{c^2}}$$

since it was assumed that a mass which was not of field origin should not vary with velocity.

However, after the appearance of the Theory of Relativity, from which it follows that a mass not of field origin *should* vary with velocity, according to this same law, just like the electromagnetic mass, this argument broke down completely in applying it to electromagnetic mass. The theory of electromagnetic mass did not explain other structural peculiarities in the electron, and only led to a number of contradictory conclusions. In the theory of the vacuum, symmetrical with respect to electrons and positrons, this electromagnetic mass reduces to zero (actually, in considering the electron as a particle, we obtain a positive value for the electromagnetic mass, but if we consider it as a "hole" we obtain a negative value).

However, the vacuum itself can be considered, to a certain extent, as a dielectric, and therefore any charge can polarise it, which, in its turn, should be reflected in the properties of the electron. According to the vacuum theory, the main mass of the electron, the so-called bare mass (m^{bare}), should not be of a "field" nature. The interaction with the vacuum introduces merely a small addition to the mass:

$$\Delta m^{\mathrm{vac}} \sim \frac{1}{137} m^{\mathrm{bare}}$$

where $\frac{1}{137} = \frac{e_0^2}{\hbar c}$ is the fine structure constant. Therefore the total mass of the electron, i.e., the experimentally observed mass, will be equal to the sum of these masses:

$$m_0 = m^{\mathrm{bare}} + \frac{b}{137} m^{\mathrm{bare}}$$

where b is a coefficient of the order of unity.

In precisely the same way, the interaction of the electron with the electron–positron vacuum leads to a reduction of the bare charge and therefore the observed charge becomes equal to

$$e = e^{\text{bare}}\left(1 - \frac{b_1}{137}\right) = -e_0$$

Up to the present time, there are no observations about the difference between the bare and the total charge.

Nevertheless, these conclusions led to an explanation of a number of facts which were well studied experimentally.

First of all, let us dwell on the Lamb shift of energy levels in the atom. According to Dirac's theory, the $2s_{\frac{1}{2}}$ level in the hydrogen atom (principal quantum number $n = 2$, orbital quantum number $l = 0$, total angular momentum quantum number $j = \frac{1}{2}$) and the $2p_{\frac{1}{2}}$ level ($n = 2$, $l = 1$, $j = \frac{1}{2}$), should coincide. However, Lamb's experiment showed that the $2s_{\frac{1}{2}}$ level should be shifted upwards relative to the $2p$ level by an amount

$$1058 \text{ Mc/s} = 1058 \times 10^6 \text{ sec}^{-1}.\dagger$$

Although this separation is very small, and in terms of wavelengths corresponds to

$$\Delta\lambda = \frac{c}{1058 \times 10^6} \approx 28 \text{ cm}$$

nevertheless it is of paramount importance, since it confirms the existence of the vacuum polarisation.

An extremely graphical picture for explaining the shift of energy levels was given by Welton. The motion of an electron, according to his theory, should be considered as the motion of a Brownian particle. It is well known that the motion of a Brownian particle

† The particularly powerful action of the vacuum only on the *s*-level can be explained in the following manner: just as in electromagnetism, the principal role in the electron–positron vacuum is played by the so-called contact interaction which, being proportional to a delta-function, is manifested only as a result of a direct overlapping of an electron and a proton. Since only for *s*-levels the wave function differs from zero at the centre of charge, they should show a maximum shift.

originates by collisions with randomly moving molecules in the surrounding medium.

In exactly the same way, the individual "shocks" of the multitudinous virtual photons, electrons and positrons forming the vacuum affect the motion of an elementary particle. This leads to the fact that the electron should begin to execute random motion in a volume with radius equal to the geometric mean of the electron radius $r_0 = e_0^2/m_0 c$ and of the Compton wavelength $\lambda_0 = h/m_0 c$,

$$R = \sqrt{r_0 \lambda_0} \approx 10^{-12} \text{ cm}$$

Consequently, although the "bare" dimensions of the electron remain for the present unknown (more precisely the "naked" electron is assumed to be a point), it "dresses in an electron–positron fur coat" with dimensions of the order of $R \approx 10^{-12}$ cm, so that the interaction between the "naked" electron and this "fur coat" is conveyed by the electromagnetic field. Having developed this idea, it is possible to explain generally the statistical nature of wave mechanics as the result of the interaction of the electron with the vacuum. It is well known that wave theory can only predict with a finite probability, determined by the uncertainty relations, the coordinates and momenta of the particle (Born's statistical interpretation). This implies that as a result of the simultaneous presence of many particles, found in an identical state, or as a result of frequently repeated identical states with different particles, the standard dispersion gives a typical wave picture of the distribution of the number of particles as a result, for example, of their diffraction (Blokhintsev–Nikolskii quantum ensemble).

The Copenhagen school of thought (Bohr, Heisenberg *et al.*) connected this dispersion with the uncontrollable action of a macroscopic observer on a microscopic object (for example, on an electron), i.e., the selfsame elements of positivism† as in the science of the micro-world are introduced.

† The uncertainty relation follows rigorously from quantum mechanics. It determines the accuracy with which the coordinate and momentum of a

However, despite this point of view, a variety of experiments are being carried out by ourselves and by foreign scientists (sometimes not entirely successfully) to find an explanation of the statistical nature of the motion of the electron without taking into account the effect of macroscopic observers on it.

We note that observers, by means of instruments, can only create conditions for a specific appearance of the wave properties of particles, for example, the diffraction of the quantum ensemble.

It appears to us that the route to the solution of this complex problem should lie in the construction of a theory where, as a result of motion of the electron, the random collisions with

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particle can be predicted theoretically. On the basis of the physical foundations of the uncertainty relation, Bohr and Heisenberg attempted to postulate the Principle of Complementarity (Copenhagen interpretation of quantum mechanics), the introduction of which is not entirely certain and, moreover, gives rise to a great deal of discussion.

Indisputably, Bohr and Heisenberg contributed a considerable amount to the development of the quantum theory. However, this does not mean that all their methodological concepts, including also the Principle of Complementarity should also be accepted completely.

According to the Principle of Complementarity, two classes of experimental equipment should exist. The one attempts to measure the space coordinates to a certain accuracy, and the other the corresponding momentum components. Since by using the first class of equipment the latter introduces an effect on the momentum, which cannot be below a certain limit, and by using the second class an effect on the coordinates is introduced, then in the opinion of the Copenhagen school there should be some ultimate limit to our knowledge of the micro-world. This assumption raises further, in particular, a principle which, if exaggerated, can say that with the disappearance of instruments the inherent wave laws of the micro-world should likewise disappear.

In general, however, the Principle of Complementarity, which rather determines not the physical laws but our philosophical outlook, can in fact find application only for explaining a certain limited circle of phenomena of the micro-world. For example, arising from the Principle of Complementarity the perfectly correct conclusion was drawn that the statistical laws of quantum mechanics should not be reduced to dynamical laws.

As regards the interpretation of the corpuscular-wave dualism, as a result supposedly of the principle of uncontrollability of the interaction between a micro-object (for example, electrons) and a macro-instrument (for example, a diffraction grating), then this question in fact remained incognisable, hidden

photons or other particles of the vacuum should be taken into account.

In particular, it was shown jointly by us and I. M. Ternov that an electron, moving in a magnetic field (for example, in the synchrotron with an energy of about 1 GeV), should begin to emit intense light quanta of high energy, which ultimately should lead to quantum excitation of betatron oscillations with a macroscopic amplitude, forming a distinctive quantal "macro-atom", which was also discovered in the extremely accurate experiments carried out by F. A. Korolev and co-workers.

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by a mask of mystery, so long as scientific investigations were confined to the limits of atomic phenomena.

Later on, extremely interesting experiments on the diffraction of flying particles showed, in turn (Vavilov, Fabrikant, Janossy *et al.*), that although at present it is possible to predict the coordinates and momenta of particles only within the limits of relative determinancy, they can be predicted experimentally quite accurately, as a rule, for a previous instant of time. Actually, the impact of an individual particle on a screen gives, instead of the theoretically predicted diffraction picture, the image of a point. What is more, experimental data emerged relating to the structure of the nucleon, defining not only its corpuscular properties, but also the interaction of pions with the vacuum (see below).

Therefore, the firm limit of cognisance of the micro-world set up by the principle of complementarity leads to positivism and cannot contribute at the present time to a further development of the science of the micro-world. In connection with this, we also recall that a mechanistic world opinion, having played such a celebrated role in some earlier stage of development of classical physics, as a result of its construction was, in the long run, to hinder the evolution of physics.

As we have already noted, having remained in the realms of quantum mechanics, it is more reasonable to imagine the quantum ensemble on the basis of an understanding of the wave-like properties of particles. The latter, even if they do not give an explanation of the statistical nature of quantum mechanics, consider this (even if for the time being only formally) as the manifestation of some objective laws of nature and do not forbid the introduction of various hypotheses, which emerge from the realm of existing quantum mechanics, in order to explain the statistical characteristics. It stands to reason that as a result of this, quantum mechanics should be considered as the subsequent and more recent stage of development of the science of elementary particles, which is not absolutely conclusive, since according to Lenin's theory of reflection, our understanding of nature should proceed along an asymptotic approach to the truth.

In the example quoted, the electrons should commence to move, according to the law of quantum theory, because of the random interaction with photons which are actually emitted. Recently, in the Frascati Laboratory (near Rome), not only has an electron-synchrotron with an energy in excess of 1 GeV been constructed, but also the first electron and positron storage device, for energies of the order of 300 MeV; these particles, moving in a magnetic field in a circular trajectory, can be retained for about two days. In these storage devices, the emission of individual electrons has already been observed, which makes it possible to follow the transition from motion according to classical laws to motion according to quantum laws.

Further, together with V. S. Tumanov, we have shown that if in Dirac's classical non-relativistic equation of motion of the electron, in which Planck's radiation friction force is taken into account (actually, this was done for a harmonic oscillator), we further take into account fluctuations in the magnetic field (virtual photons), then we obtain automatically the relationship between the indeterminancy for the theoretically-predicted joint scattering of the coordinates and the momentum. According to this hypothesis, the motion of the electron should, in general, be considered as the motion of a Brownian particle, when theory can predict only the probability of one or other trajectory, since the motion of the electron is connected, on the whole, with the vacuum fluctuations.

Thus, it is possible to choose in classical theory some closed system containing a finite number of point particles (or a finite number of degrees of freedom), for which, in principle it should be possible to formulate precise classical equations of motion (dynamic or Laplacian law), and to identify causality with a single-valued prediction. It is impossible to do this in quantum field theory, since even a single electron will contain a finite number of degrees of freedom, taking into account random collisions with the vacuum.

In other words, if, on the basis of behaviour of individual

particles, the motion of all of them is studied in classical theory (classical statistical physics), then in quantum mechanics, on the other hand, on the basis of statistical laws attempts are made to visualise the motion of the individual particle.

Let us dwell further on the vacuum contribution to the magnetic moment of the electron. The effect of the electron–positron vacuum can be visualised particularly clearly as a result of the determination of the total magnetic moment of the electron. Taking into account the electron–positron vacuum, the observed magnetic moment of the electron should be equal to:

$$\mu^{el} = -\mu_0\left(1 + \frac{1}{137} \times \frac{1}{2\pi}\right) = -\mu_0(1 + 0{\cdot}00116)$$

The second term in the brackets, proportional to 0·00116, is practically a thousand times less than the main term, and defines the vacuum contribution to the magnetic moment of the electron, dependent upon the electron–positron "fur coat". In complete numerical agreement with theory, this correction was observed experimentally in the classical experiments of Kusch and Foley.

An analysis of the expression for the magnetic moment is also of further interest in this respect, in that we can by means of it determine not only theoretically but also experimentally how far the electron–positron vacuum is involved, and we can essentially consider elementary particles to be not "naked", but dressed in vacuum "fur coats".

3

Nucleons and Pions (Nuclear Field Quanta)

THE binding energy of nucleons (i.e., protons and neutrons) in the nucleus is mainly due to specific nuclear forces, which are of a short-range nature, i.e., at nuclear distances of the order of 10^{-13} cm they exceed Coulomb forces by a factor of a thousand, but at greater distances they fall practically to zero. In this connection, nuclear forces remind us of the cohesive forces, retaining liquid droplets in a spherical state. The question of nuclear forces remained open for a long time.

Finally, Yukawa in 1935 suggested that nuclear field quanta exist (Yukawa himself called them *i*-particles; subsequently they were shown to be pions).

If the rest mass of free spinless particles is non-vanishing, then the corresponding wave equation should have the form:

$$(E^2 - c^2 p^2 - m^2 c^4)\varphi = 0 \tag{1}$$

where $E = -\frac{\hbar}{i} \times \frac{\partial}{\partial t}$ and $\rho = \frac{\hbar}{i} \nabla$ are the energy and momentum operators. Hence, in particular in the stationary case, when the function φ is independent of time, we obtain Yukawa's equation for the nuclear potential:

$$(\nabla^2 - k_0^2)\varphi = 0, \qquad m = \frac{\hbar k_0}{c}$$

If the mass of the particles constituting the field be put equal to zero, we obtain the usual Poisson equation for an electrical field, $\nabla^2\varphi = 0$, which leads to the following expression for the energy of interaction between the proton and the electron:

$$V = -\frac{e_0^2}{r}$$

The solution of Dirac's equation, with non-vanishing rest mass (for pions), gives, for the energy of interaction between two nucleons, the expression

$$V = -g^2 \frac{e^{-k_0 r}}{r} \tag{2}$$

We find, by choosing g^2 of the order of $1000\, e_0^2$, that at small distances

$$r \ll \frac{1}{k_0} = \frac{\hbar}{mc}$$

the nuclear forces will exceed the electromagnetic forces by more than a thousand times.

At distances exceeding the value of $\hbar/mc$, the nuclear forces, owing to the presence of the exponential factor, are practically reduced to zero.

Knowing the range of the nuclear forces, the value of $\hbar/mc$ can be determined, and at the same time also the mass of the pions. Recently neutral mesons (π^0-mesons with a mass of 264 m_0) have been discovered as well as charged mesons (π^+-mesons with a mass of 273 m_0).

Their existence was predicted by Yukawa in 1935, but they were discovered only in 1947 by the English physicist Powell.

According to modern quantum field theory, the interaction between two elementary particles takes place owing to the exchange of a third particle.

Without going into the details of this theory, we still point out that the electrostatic interaction is caused by the emission and absorption of the charges of the so-called pseudo-photons, representing quanta of the longitudinal electromagnetic field.

Precisely in the same way, the nuclear forces according to Yukawa's theory originate as a result of the fact that two nucleons exchange pions with one another.

This interchange also binds nucleons together in the nucleus, causing them to adhere securely together, as usually happens with any mutually beneficial interchange.

It should be noted that the theory of nuclear forces is considerably less well developed than the theory of electromagnetic forces. The exact form of the interaction between a proton and a neutron is still unknown. However, the existence of a meson "fur coat" has already been detected experimentally by studying the scattering by nucleons of fast charged particles (electrons, pions).

Energy, as a rule, is measured in electron-volts (1 eV is the energy acquired by an electron in moving through a potential difference of 1 Volt), mega-electron volts (1 MeV = 10^6 eV) and in giga-electron volts (1 GeV = 10^9 eV).† Thus, for example, the binding energy of the electron in the hydrogen atom is equal to 13 eV. The energy holding atoms in a molecule is a few electron volts.

The characteristic energy of the electron, $m_0 c^2$, is equal to approximately 0·5 MeV, so that as a result of the annihilation of an electron and a positron energy is released in the form of gamma-radiation exceeding 1 MeV. Alpha-particles, which are shot out from radioactive uranium nuclei, have an energy of about 7 MeV. These particles were also used by Rutherford for shooting through the atom and thus establishing the planetary model.

Finally, in order to bombard nucleons, it is necessary to take particles with even higher energies, of the order of hundreds of mega-electron volts, or several giga-electron volts. Particles with such high energies are to be found, for example, in cosmic rays (their average energy is 10 GeV). However, they are relatively few in number. A considerably larger number of particles with

† The Americans often call a GeV a BeV (for billion eV; 1 billion (American) = 10^9).

high energy can be obtained in accelerators. In particular, many of the internal properties of the proton were determined by bombarding them with high-speed electrons and pions.

Let us dwell first of all on Hofstadter's experiments, in which protons and neutrons were bombarded with electrons having energies of up to 600 MeV (these high-speed electrons were obtained in the Stanford linear accelerator), and on Wilson's experiments which, using the Cornell University electron–synchrotron, increased the energy of the electrons to 1·3 GeV.

Such high-speed electrons were found to be extremely advantageous for studying the structure of nucleons, since they do not interact nuclear-wise with nucleons (we assume that the electromagnetic forces are a thousand times weaker than the nuclear forces), they could penetrate deep into the nucleon and give information concerning its electromagnetic structure. The distribution of the electrical charge in the nucleon and its magnetic moment are characterised by the curves depicted in Figs. 5 and 6 respectively.

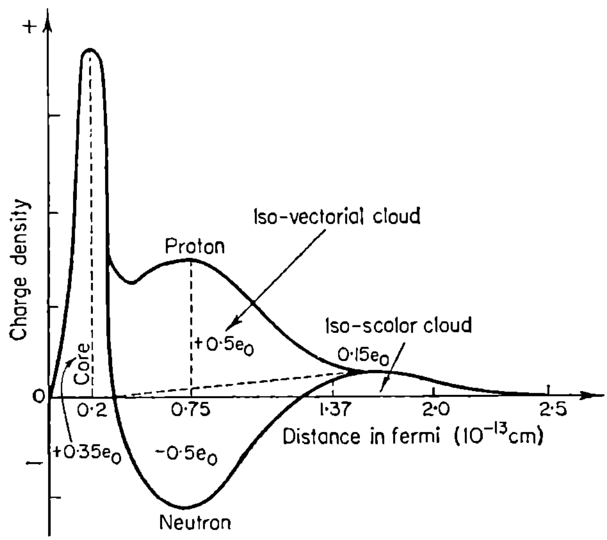

FIG. 5. *Distribution of electrical charge in the nucleon. The iso-vectorial cloud, evidently consists primarily of ρ-mesons (union of two pions), and the iso-scalar cloud of omega-mesons (union of three pions).*

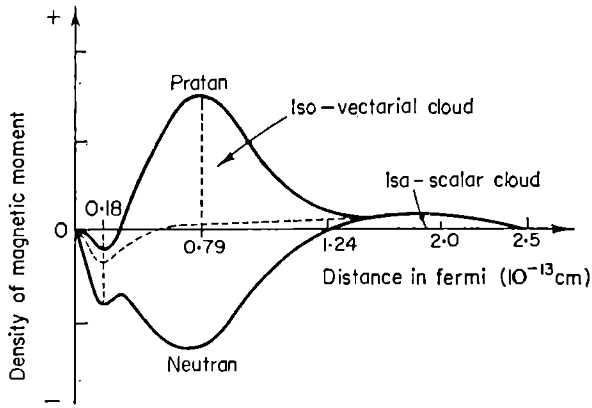

FIG. 6. *Distribution of anomalous magnetic moment in the nucleon.*

It can be seen from these curves, that the nucleon is not a point-like particle. It consists of a core (i.e., the densest part, where the bulk of the mass is concentrated), which is charged positively for the neutron just as for the proton, and two clouds, evidently consisting of pions (Table 1).

TABLE ONE

Distribution of Charge and Magnetic Moment in the Nucleon

	Charge (e_0)	*Mean-square radius for charge distribution (fermi)*	*Anomalous magnetic moment (pauli)*	*Mean-square radius for distribution of magnetic moment (fermi)*
"Core"	0·35	0·2	−0·11	0·18
Iso-vectorial cloud	±0·50	0·75	±1·00	0·79
Iso-scalar cloud	0·15	1·37	0·08	1·24

1 fermi = 10^{-13} cm; 1 pauli = $\frac{1}{2}(\mu_p-\mu_n-\mu_{\text{nucl}}) = 1{\cdot}85\ \mu_{\text{nucl}}$

where

$$\mu_{\text{nucl}} = \frac{e_0 h}{2Mc^2} = \frac{1}{1836}\mu_0$$

μ_0 is the Bohr magneton and M is the mass of the proton.

Although the curves of the distribution of electrical charge and anomalous magnetic moment differ somewhat, they have the same mean-square radius of about 0·8 fermi. The shell lying directly next to the core bears the name of iso-vectorial shell, since the sign of the charge is changed as a result of transition from proton to neutron. The second, more remote shell is called the iso-scalar shell. It has the same positive charge for the proton as for the neutron.†

By the aid of the meson "fur coat", it is possible first of all to try to explain the phenomenon of the anomalous moment of the nucleon.

Actually, Dirac's wave equation (without taking into account the vacuum) gives a magnetic moment equal to

$$\mu_{\text{nucl}} = \frac{e_0 \hbar}{2Mc}$$

for particles with spin $\frac{1}{2}$, charge e_0 and mass M.

Therefore, according to this theory, the magnetic moment of the proton should be exactly equal to the nuclear magneton, but the magnetic moment of the neutron should, in general, be absent since its charge is equal to zero.

At the same time, the experimental value of the magnetic moment of the proton amounts to 2·8 nuclear magnetons, i.e., 1·8 units greater than anticipated, and for the neutron, instead of zero we obtain 1·9 nuclear magnetons.

Thus, we have:

$$\mu_p = \mu_{\text{nucl}}(1+1{\cdot}8)$$
$$\mu_n = \mu_{\text{nucl}}(0-1{\cdot}9)$$

The first term in the brackets corresponds to the Dirac magnetic moment of the nucleon, and the second characterises the anomalous magnetic moment, due to the meson "fur coat". We can see that if in the theory of the electron, the vacuum portion amounts

† According to recent data, the iso-vectorial shell consists of rho-mesons (union of two pions), and the iso-scalar shell consists of omega-mesons (union of three pions).

to about one-thousandth part of the Dirac magnetic moment, then in the theory of the nucleon, the vacuum portion for the proton exceeds its Dirac moment approximately by a factor of two, and for the neutron it determines, in general, the whole of its magnetic moment.

It is of great interest to set up experiments which would permit us both to produce and to observe the deformation of the meson "fur coat" of the proton. For this it is necessary first of all to create very powerful electromagnetic fields, capable of considerably deforming the protons. It may be possible to exert these fields by means of a laser beam, the light energy from which can be focused and made a thousand times greater than the sun's rays by means of special telescopic apparatus.

It is well known, that as a result of the passage of electrons through atoms the electrons, in the case of relatively small energies, interact principally with the electrons of the atomic shell. In this case, resonance phenomena should be observed (we recall, for example, the Franck–Hertz experiments, when resonance regions were discovered as a result of scattering of electrons by mercury atoms in the 4·9 eV energy range). With larger energies, of the scattered electrons, the latter will interact with atomic nuclei, when resonance phenomena should no longer be present.

In exactly the same way, as a result of scattering of relatively slow pions by nucleons (with energies of 100–1500 MeV), the latter will interact with the pion cloud, forming the nucleon shell. In this case, as a result of scattering of π^+-mesons by protons, resonance regions will be observed for a kinetic energy of 180 and 1330 MeV (Fig. 7).†

As a result of the scattering of π^--mesons by protons, the resonances will correspond to kinetic energies of 180, 605 and

† The barn is the unit of cross section, equal to 10^{-24} cm^2 (the millibarn is equal to 10^{-27} cm^2).

The choice of this value is associated with the fact that the geometrical cross sections of atomic nuclei are about 10^{-24} cm^2. A cross section of 1 barn denotes that in the presence of one such nucleus, of 10^{24} particles incident on unit area, one particle will be absorbed.

890 MeV (Fig. 8). At higher energies (several thousands of MeV) the pions will be scattered by the core, i.e., by a nuclear nucleon, when resonance phenomena should no longer be observed.

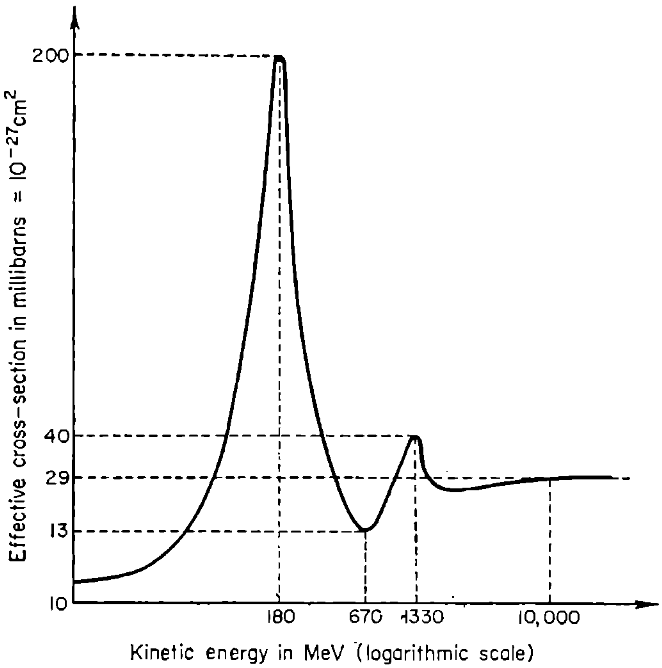

FIG. 7. *Resonances resulting from scattering of π^+-mesons by protons, in the laboratory system (original proton at rest).*

As we have shown, the fundamental characteristics of elementary particles are first of all their rest mass, electrical charge and spin. We can confine ourselves entirely to these characteristics in the case where we are dealing only with electromagnetic interactions (for example, in the atom).

The spin determines the statistics of the particles (particles with half odd-integral spin obey Fermi statistics and are called "fermions"; particles with integral spin obey Bose statistics and are called "bosons"), and also the number of possible states, which is characterised by a different z-component of the spin.

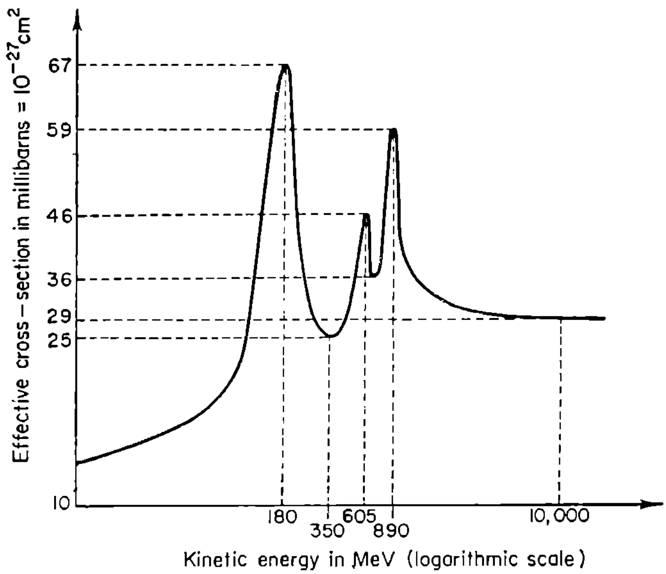

FIG. 8. *Resonances resulting from scattering of π^--mesons by protons in the laboratory system.*

If the spin is equal to zero ($s = 0$), then, obviously only one state is possible ($s_z = 0$). For particles with spin $\frac{1}{2}$, two states are possible:

$$s_z = -\tfrac{1}{2}, \qquad s_z = +\tfrac{1}{2}$$

For particles with $s = 1$, there are three states:

$$s_z = -1, \qquad s_z = 0, \qquad s_z = +1$$

and so on.

If, for example, a hydrogen atom is put into a magnetic field, then to the nuclear Coulomb energy of attraction, which is practically independent of spin, a small energy value ΔE is added, due to the magnetic interaction, which will depend on the direction of the spin:

$$\Delta E = -\frac{eH\hbar}{m_0 c} s_z$$

where $s_z = \pm \frac{1}{2}$.

As a result of investigations of the motion of nucleons within the nucleus, nuclear forces are found to play the primary role, and they are so-called strong interactions, since they exceed the electromagnetic forces at small distances (10^{-13} cm) by approximately a factor of 1000. The nuclear forces acting between two protons or two neutrons, or between a proton and a neutron, turn out to be equal to one another (charge independence). A calculation of the electromagnetic field gives a small correction to the total force, just as the magnetic field within the atom gives a relatively small correction to the Coulomb interaction, depending on the direction of the spin.

Consequently, Heisenberg proposed that the proton and the neutron should be considered as a single particle (similar to two electrons with oppositely directed spins), and that a new variable should be introduced (by analogy with the spin of the electron)—the so-called isotopic spin (or isospin), which will characterise the electrical distinction between the proton and the neutron, which is unimportant in comparison with the nuclear forces acting between them.

The word "isotopic" signifies first of all that a proton and a neutron form a single isotopic species, i.e., they have identical nuclear charge and practically identical mass. The word "spin" reflects the identity of the mathematical description of isotopic and normal spin.

By analogy with ordinary spin, the isotopic spin of an isotopic species consisting of two states, is chosen equal to $\frac{1}{2}$ ($I = \frac{1}{2}$), since by analogy with the z-component of the spin, the component of the isotopic spin in the given case in some arbitrary isotopic space may assume two values: $I_3 = -\frac{1}{2}$ for the neutron, and $I_3 = +\frac{1}{2}$ for the proton.

For pions the primary interaction is nuclear. Consequently they too may be combined into a single isotopic species. Since there are three types of pions, then the isotopic spin should be equal to unity, so that for π^--mesons $I_3 = -1$, for π^0-mesons $I_3 = 0$ and for π^+-mesons $I_3 = +1$.

By analogy with the discovery of the positron (antiparticle of the electron), it was natural to expect that together with nucleons (protons and neutrons) there should exist also antinucleons (antiprotons and antineutrons). Antiprotons should differ from protons, for example, in the sign of the electrical charge, and antineutrons from neutrons by the sign of the magnetic moment (we recall that the neutron has a magnetic moment antiparallel to the spin and consequently has a negative sign, and for the antineutron these moments should be parallel).

However, the sign of the charge does not characterise the basic difference between the antiproton and the proton, since in the theory of nucleons, the principal role belongs not to electromagnetic forces but to nuclear forces.

Antinucleons were successfully discovered by Segré, Chamberlain *et al.* relatively recently, when the 6 GeV accelerator in Berkeley (U.S.A.) was constructed—the so-called betatron. The difficulty in discovering them was associated with the fact that the energy even at rest of the nucleon and antinucleon amounts to about 2 GeV. More precise calculations show that the probability of occurrence of a nucleon–antinucleon pair becomes appreciable when protons with an energy of not less than 6 GeV strike the target.

In order to describe the basic difference between nucleons and antinucleons, it was necessary to introduce a special baryon number B, assuming $B = +1$ for nucleons, and $B = -1$ for antinucleons. For the remaining, lighter particles (pions, electrons, etc.), $B = 0$.

It should be noted in connection with this, that the electrical charge in practice plays two roles in the theory of elementary particles. Firstly, it defines the magnitude of the Coulomb interaction. Secondly, in all processes associated with the occurrence of annihilation of elementary particles, the electrical charge should be strictly conserved.

In the theory of elementary particles, the second special feature of the electrical charge is frequently of most interest. In

order to describe the second special feature, the elementary charge e_0 can be chosen as the unit of charge. Then, for the electron and antiproton the electrical charge is $Q = -1$, and for the positron and proton $Q = +1$ and, finally, for the neutron and antineutron $Q = 0$.

In all reactions, the Law of Conservation of Electrical Charge should be strictly observed:

$$\sum Q = \text{constant}$$

Actually, the electron should always be born with the positron, and the proton with the antiproton. However, the Law of Conservation of Electrical Charge is clearly inadequate, since it does not prohibit, for example, the birth of two neutrons.

In the birth of nucleons, a second law should further be strictly observed, namely the Law of Conservation of Baryon Number:

$$\sum B = \text{constant}$$

which is even more important in the theory of nucleons, since as a result of collision of a proton and a neutron, their transformation is forbidden into lighter particles (for example, into π^+- and π^0-mesons) although from the Law of Conservation of Electrical Charge only, this transformation should be quite possible.

It follows from the Law of Conservation of Baryon Number that nucleons are stable particles, and only as a result of collision with antinucleons may they be transformed into lighter particles. In precisely the same way, the simultaneous birth of two neutrons is quite inadmissible. Neutrons may be born together with antineutrons, when the Law of Conservation of Baryon Number is observed.

4

Beta-Disintegration and the Discovery of the Neutrino

THE most recent development of the science of elementary particles is associated with the discovery of the neutrino.

The neutron can exist inside stable nuclei for an indefinite length of time. In the free state, the neutron is an unstable particle with a half-life of approximately 12 minutes (the lifetime is equal to $12/\ln 2 \approx 17$ min ≈ 1000 sec). Further, as a result of beta-disintegration, the mass of the neutron which is transformed into a proton is reduced by an amount corresponding to an energy of $2{\cdot}5\ m_0 c^2$, and at the same time the electron, because of its intrinsic energy ($m_0 c^2$), flies off with various energies, commencing at $m_0 c^2$ and terminating at $2{\cdot}5\ m_0 c^2$. The average energy of the electrons is equal to only $1{\cdot}5\ m_0 c^2$, i.e., in every disintegration event an average energy of about $m_0 c^2$ is released. Moreover, it should be added further, that all processes taking place within the atom and within the atomic nucleus should be, as a rule, discrete. The light emitted by the atom forms monochromatic lines. Alpha-particles emitted from the nucleus possess a definite energy, etc. Consequently, for a long time the continuity of the beta-spectrum remained completely incomprehensible. On this basis, a number of eminent physicists, amongst

them Niels Bohr, were speaking generally at one time of the fact that in the micro-world the Law of Conservation of Energy cannot and does not hold. In order to explain the apparent loss of energy, Pauli put forward a hypothesis in 1930, according to which this loss of energy resulting from beta-disintegration is carried away by some other particle, which was given the name of "antineutrino", i.e., the beta-decay reaction is of the form:

$$n \rightarrow p + e^- + \bar{\nu}$$

Similarly, a neutrino is formed as a result of positron decay:

$$p \rightarrow n + e^+ + \nu$$

For a long time it was not clear how to differentiate between a neutrino and an antineutrino. However, this distinction was later established. We shall dwell on this problem somewhat later on. Meanwhile we shall define the antineutrino as a particle which is formed by the decay of a neutron, and the neutrino as a particle which is formed by the decay of a proton.† These beta-transformations occur extremely rarely and are due to the so-called weak interactions.

Thus we have three types of interactions: strong, depending on nuclear forces, electromagnetic and, finally, weak interactions depending, for example, on the decay of a neutron, not counting gravitational interactions which we shall not consider here.

The neutrino, and also the antineutrino, possess great penetrating power, and therefore these particles remained totally unobserved for a long time.

The neutrino is capable of penetrating the earth, the sun, stars with a mass exceeding many times the mass of the sun, etc. It was

† In order to describe this difference, a lepton charge can be introduced formally, which is equal to plus unity (+1) for a neutrino and an electron, minus unity (−1) for the antineutrino and the positron, and zero for nucleons. Therefore, in order that the lepton charge should be conserved in beta-decay reactions, the electron should always appear together with the antineutrino and the positron with the neutrino. The introduction of the neutrino leads not only to conservation of energy, but also to conservation of spin in beta-decay.

only in 1957 that Reines and Cowan succeeded in detecting the antineutrino, when powerful sources of these elusive particles were built (a reactor with a power of 300 Megawatts). This reactor, according to theoretical calculations, should emit 10^{19} antineutrinos each second, and at a distance of 10 metres from the reactor approximately 10^{13} antineutrinos (i.e., ten thousand thousand million) should fall on each square centimetre per second.

The antineutrino was captured by protons of hydrogen-containing substances according to the reaction, which is the reverse of beta-decay†:

$$\bar{\nu}+p \rightarrow n+e^{+}$$

A ton of water absorbed only a few particles of the powerful stream of antineutrinos and approximately 100 transformations per hour occurred of a proton into a neutron and a positron (the effective cross section was found to be equal to about 10^{-44} cm^2). This reaction was recorded by two photocells which registered the scintillations. The first scintillation was the positron and the second scintillation was the gamma-quantum which originates as a result of capture of a neutron by a hydrogen atom. The experiments were of such a precise nature that for their preparation and execution, more than five years were required.

As a result of thermo-nuclear reactions taking place in the sun, a neutrino is formed, and not an antineutrino, since the final result of these reactions is the transformation of four protons into helium (as in the case of the hydrogen cycle, so also in the case of the Bethe cycle)

$$4p \rightarrow {}_2\mathrm{He}^4+2e^{+}+2\nu$$

so that the total number of neutrinos amounts to several per cent of the entire energy radiated by the sun.

In connection with the discovery of the neutrino, neutrino

† We note that as a consequence of conservation of lepton charge, the neutrino (i.e., the particle formed as a result of decay of a proton) cannot be captured according to this reaction.

analysis of heavenly bodies acquired particular importance, and first in line was the sun. The fact is that for a long time we had obtained our knowledge of the sun by studying the light spectrum of the sun, the flow of cosmic particles, and also the recently discovered radioemission. All this enables us to study only the properties of the sun's envelope. Since the neutrino passes through the sun quite freely, then the neutrinos which fall on the earth will thus originate from reactions which take place within the interior of the sun. It should be anticipated that on the average, 10 000 million (10^{10}) antineutrinos fall on to one square centimetre per second, i.e., one thousand times less than from the nuclear reactor of Reines and Cowan's experiments. Since hydrogen absorbs only antineutrinos, it is necessary to use other substances for collecting the neutrinos. Several tens of tons of relatively cheap carbon tetrachloride can be used as a target for capturing the neutrino. Absorption of a neutrino should take place according to the reaction †

$$\nu + Cl^{37} \rightarrow e^- + Ag^{37}$$

Recently in Dubna, experiments were discussed for capturing solar neutrinos. The main difficulty of the experiment will consist in knowing how to record single events of neutrino detection. Naturally this will require the construction of complex and more precise instrumentation, as compared with the equipment used by Reines and Cowan.

Neutrino analysis has an enormously promising future, since the all-pervading neutrino is, as we might say, the living witness of the formation of new stars and generally of our entire galaxy. The astrophysicist, undisputedly, will attach a great future to the neutrino.

† The effective capture cross section of an individual neutrino emitted by the sun should be approximately the same as in Reines and Cowan's experiments, since the energy of the neutrino in both cases is of the order of several MeV. However, if it were possible to obtain a neutrino with an energy of several GeV, then the effective capture cross section would be sharply increased.

5

The Problem of Non-conservation of Parity

ASSOCIATED with the discovery of the antiparticles, the question of the artificial formation of anti-atoms arises. Around the nucleus of the anti-atom, consisting of antiprotons and anti-neutrons, positrons should revolve. As a result of collision of atoms and anti-atoms, their transformation into light quanta, pions (nuclear quanta), and so on, should be anticipated. If the collision occurred of a mass consisting of a substance and an anti-substance or, as we sometimes say, a "world" and an "anti-world", then the energy liberated should exceed the energy liberated as a result of nuclear reactions by a factor of a thousand. Actually, the energy formed in the first case would be equal to $2Mc^2$, where M is the total mass of the anti-substance, whilst as a result of nuclear reactions even in the best case only a fraction of a per cent of the intrinsic energy of the nucleus is liberated.

However, if anti-atoms and atoms could be isolated from each other, then they might exist for as long as we desire and therefore some scientists do not exclude the possibility of the existence of anti-worlds, consisting of anti-atoms.

At first glance it can be seen that all physical phenomena occurring in an isolated anti-world, should be completely identical with the corresponding phenomena observed in the world surrounding us, since the transition from world to anti-world,

leading to a change of all electrical and nucleonic charges into their opposites, would not be able to change the magnitude of the electromagnetic and nuclear forces acting between particles. In particular, the spectral lines emitted by hydrogen and anti-hydrogen should be completely identical and a spectroscopist would not only be unable to differentiate between them, but he would not even be able to indicate a method for doing this.

However, recently Lee and Yang made an extremely important discovery, known under the name of non-conservation of parity, which enables the asymmetry of certain physical phenomena occurring in the world and in the anti-world to be located. This asymmetry was first discovered as a result of the disintegration of particles with the participation of a neutrino. It was supposed initially that the neutrino cannot in any way be distinguished from the antineutrino (Majorana's hypothesis). This should imply, for example, that a neutron can not only emit an anti-neutrino, but also together with a neutrino can absorb an antineutrino.

However, experiments showed that an antineutrino cannot be absorbed by a neutron. This conclusion was made on the basis of negative experimental results on double beta-decay, in which it was shown that the emission by a nucleus of only two electrons without an antineutrino is impossible: one neutron emits an electron and an antineutrino, and the other should absorb this antineutrino and emit a second electron.

By introducing the Law of Conservation of Lepton Charge, it is possible to understand why, as a result of the decay of a neutron, an antineutrino should be emitted (and not a neutrino), and at the same time why the neutron can absorb only a neutrino, i.e., the particle emitted by a proton.

We shall consider in more detail the question of the possibility of the manifestation of an asymmetry in physical phenomena in the micro-world as a result of the charge conjugate transformation (C-transformation), i.e., through the substitution of all charged particles by the corresponding antiparticles.

In order that asymmetry should be manifested as a result of a C-transformation, it is necessary somehow to introduce non-invariance relative to the C-transformation into the initial equations. This non-invariance should not violate both rules of transformation, upon which the basic equations describing the motion of the elementary particles are dependent. Transformations which should be related to the number of permissible equations are those which conserve the invariance of the theory under a Lorentz transformation and which satisfy the Lüders–Pauli CPT-Theorem.

According to the CPT-Theorem, the wave equations should conserve their invariance by the simultaneous accomplishment of three transformations: (a) space inversion, i.e., as a result of changing from a right-hand system of coordinates into a left-hand system (P-transformation; P for parity). As a result of this all three space component vectors, for example the radius vector $\boldsymbol{r}$, and the vector potential A, change their sign ($\boldsymbol{r} \to -\boldsymbol{r}$, $A \to -A$); (b) time reversal (T-transformation), when the time t and also the fourth component of four-vectors (for example, the scalar potential Φ) change their sign ($t \to -t$, $\Phi \to -\Phi$); (c) charge conjugate transformation (C-transformation), when electrons are replaced by positrons, and so on. In particular, in the case of the presence of an electromagnetic field only, the charge conjugate transformation leads simply to a change in sign of the electrical charge.

As an example, let us consider the invariance of the relativistic Lagrangian function of classical electrodynamics:

$$L = -m_0 c^2 \sqrt{1 - v^2/c^2} - e\Phi + \frac{e}{c}(A \cdot \boldsymbol{v})$$

where $\boldsymbol{v}$ is the velocity of the moving electron. Obviously, this function conserves its invariance relative to the Lorentz transformation, and also relative to a space inversion ($A \to -A$, $\boldsymbol{v} \to -\boldsymbol{v}$).

However, it will not conserve its invariance relative to the

T-transformation $\left(\Phi \to -\Phi, \boldsymbol{v} = \dfrac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} \to -\boldsymbol{v}\right)$ and to the C-transformation ($e \to -e$) separately. Only the joint CT-transformation, together with the joint CP-transformation will conserve the invariance of the Lagrangian function L. Therefore this Lagrangian expression is quite permissible for classical physics from the point of view of the general theory of wave equations.

The joint $CT(=T')$-transformation is called a weak time reversal (as distinct from the T-transformation which is called a strong transformation), and the $CPT(=R')$-transformation is called the weak four-dimensional reflection of space and time. Thus, the equations of classical electrodynamics, and likewise, as we shall show later, also the equations of any relativistic field theory should conserve their invariance relative to the weak four-dimensional reflection (R'-transformation).

The asymmetry of the neutrino wave equation relative to a C-transformation was introduced by Lee and Yang in 1956. As a result of this they proposed that the neutrino differed from the antineutrino not only in lepton charge (non-violation of symmetry as a result of C-transformation), but also in helicity, i.e., the sense of the circular polarisation. According to this theory, the neutrino should itself be considered as a photon, having a left-handed circular polarisation (left-handed particle), and the antineutrino as a right-handed polarised photon (right-handed particle).

The difference between the neutrino and polarised photons consists only in the value of their spin. For the photon the spin is equal to unity (in units $\hbar$), and for the neutrino the spin is equal to one-half.

The neutrino (particle with $E > 0$) and the antineutrino (antiparticle, i.e., a "hole" in the background of particles with $E < 0$) are shown in Fig. 9. It can be seen from this figure that for particles with left-handed helicity (neutrino), as a result of screwing in the direction of the momentum, its rotation will

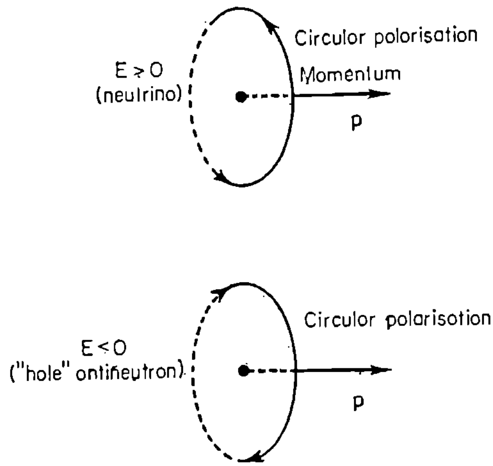

FIG. 9. *Helicity of the neutrino and antineutrino.*

coincide with the direction of polarisation,† if the thread of the screw is left-handed (see upper figure). The right-handed antineutrino is shown in the lower figure.

In order to describe the new property of the neutrino with a rest mass exactly equal to zero, Weyl's two-component equation can be used, generally speaking. However, this equation does not remain invariant as a result of transition from a right-handed system of coordinates into a left-handed system. The latter was interpreted by Lee and Yang, and also by Landau, as a transition resulting from the P-transformation of a left-handed neutrino into a right-handed neutrino, i.e., into a non-existent state.

In order that the right-handed neutrino should again be made existent, they proposed that the P-transformation should be further supplemented by a C-transformation. Then, as a result of these two joint transformations, the left-handed neutrino should be converted into a real right-handed antineutrino. Symbolically, this can be written in the form $CP =$ constant.

† In optics, on the contrary, the screw is screwed in *from* the observer, i.e., contrary to the motion of the photon and therefore a left-handed photon is called a right-handed polarised photon. However, this concept is not used, as a rule, in the modern theory of elementary particles.

They called this latter transformation a combined inversion.

If this point of view were shown to be correct, then the well-known Law of Non-conservation of Parity would be represented as the synthesis of observer and particle, and in this respect it should be considered as the Copenhagen interpretation of the corpuscular-wave dualism.

Actually, the choice of a right-handed or a left-handed system of coordinates depends exclusively on the wiles of the observer, and therefore it can say nothing at all about the properties of elementary particles. Therefore, as a result of a P-transformation, left-handed particles should remain left-handed, and only the mathematical form can be changed for describing a left-handed particle.

Non-conservation of parity, discovered by Lee and Yang, made it possible, of course, to give the correct theory of disintegration of particles with neutrino participation. At the same time, the interpretation of this phenomenon by means of the combined inversion gives rise to serious objections by us.

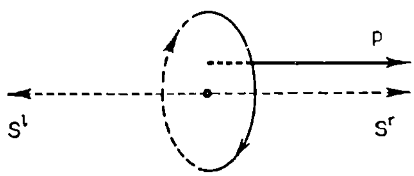

FIG. 10. *Right-handed polarised particle: p—momentum (polar vector), s^r—unit spin vector in the right-handed system (axial vector), s^l—unit spin vector, describing the same polarisation in the left-handed system.*

We shall attempt to give another interpretation of non-conservation of parity, using simple geometrical considerations. For this purpose we shall write the right-handed helicity in a right-handed and a left-handed system of coordinates.

It can be seen from Fig. 10 that the right-handed helicity in the right-handed and left-handed systems of coordinates is described by oppositely-directed axial spin vectors.

In the right-handed system of coordinates, the axial vector is parallel to the momentum:

$$s^r = \frac{(s^r . p)}{p} = 1$$

in the left-handed system it is antiparallel:

$$s^l = \frac{(s^l . p)}{p} = -1$$

In precisely the same way, for describing left-handed helicity we have:

$$s^r = -s^l = -1$$

It would be incorrect to interpret the change in sign of the component of the axial spin vector in the direction of the momentum, as a result of a transition from a right-handed system of coordinates to a left-handed system, as a change in the helicity itself.

In order to illustrate our ideas, we shall introduce the following example. Suppose that observers are flying on the airscrews of an aircraft, the propellers of which are describing a right-handed screw relative to the velocity of the aircraft. The observers who select the right-handed system of coordinates for their investigations will maintain that the angular velocity (axial vector) is parallel to the velocity of motion of the aircraft (polar vector). Other observers, who selected a left-handed system of coordinates (i.e., from the point of view of the first observers they execute a P-transformation) will maintain the reverse—that the angular velocity is antiparallel to the velocity of motion of the aircraft, although the actual physical process which these and the other observers describe by different mathematical methods will be one and the same, namely, the right-handed motion of the propeller.

We can describe the properties of the polarised neutrino if the wave function of the Dirac equation

$$(E - c\rho_1(\sigma . p) - \rho_3 m_0 c^2)\psi = 0 \tag{3}$$

where the ρ_n and $\boldsymbol{\sigma}$ are the familiar Dirac matrices, and E and $\boldsymbol{p}$ are the energy and momentum operators, further satisfies the supplementary condition:

$$\frac{(\boldsymbol{\sigma} \cdot \boldsymbol{p})}{p}\psi = s\psi \tag{4}$$

Let us examine, for example, the solution corresponding to the assumed energy and momentum, parallel to the z-axis:

$$\psi = b\, e^{-iEt+ipz}$$

where, for the sake of simplicity, we assume that $\hbar = 1$. Then, introducing the components of the polarisation vector, in a direction perpendicular to the momentum, $b_x = \sigma_1 b$ and $b_y = \sigma_2 b$, we obtain

$$b_y = isb_x \tag{5}$$

Hence it can be seen that for a right-handed antineutrino ($\bar{\nu}$) $s^r = -s^l = 1$, and for a left-handed neutrino (ν) $s^r = -s^l = -1$.†

In order that not only Dirac's equation but also the supplementary condition (4) (together also with the helicity) should remain invariant under a Lorentz transformation, it was necessary to assume, just as in the two-component theory, that the mass of the neutrino is exactly equal to zero.

In future, we shall consider a transformation to be invariant if it conserves helicity in the case of both the neutrino and the antineutrino, notwithstanding the fact that as a result of the transformation the mathematical form for describing the helicity can be changed.

Just as in the case of classical electrodynamics, the equation for the polarised neutrino remains invariant, not only relative to a P-transformation but also relative to a joint CT-transformation, i.e., a weak time-reversal.

In order to show this, we refer the state with positive energy to the neutrino (amplitude or operator b_ν), and the state with

† According to the four-component theory, a second solution is also possible, when the neutrino (ν') is right-handed, and the antineutrino ($\bar{\nu}'$) is left-handed.

negative energy to the antineutrino (operator $b_{\bar{\nu}}^{+}$):

$$\psi = b_\nu(\boldsymbol{p}_\nu, s_\nu^r)\, e^{-iE_\nu t + i(\boldsymbol{p}_\nu \boldsymbol{r})} + b_{\bar{\nu}}^{+}(\boldsymbol{p}_{\bar{\nu}}, s_{\bar{\nu}}^r)\, e^{iE_{\bar{\nu}} t - i(\boldsymbol{p}_{\bar{\nu}} \boldsymbol{r})} \tag{6}$$

We select the initial momenta of the neutrino and antineutrino parallel to one another

$$(\boldsymbol{p}_\nu = \boldsymbol{p}_{\bar{\nu}} = \boldsymbol{p})$$

and we select the helicities different from one another

$$(s_\nu^r = -\, s_{\bar{\nu}}^r = -\, 1)$$

With regard to the second-quantised operator b_ν, being the multiplier of the exponent e^{-iEt}, it should be assumed to be an annihilation operator, since, being multipled by the conjugate operator (i.e., the quantity b^+b) it gives a non-vanishing value, when there is a single particle in the first instant. In the case when there are no particles, the value of b^+b is equal to zero. In exactly the same way, the operator b^+, being the multiplier of the exponent e^{iEt}, is a creation operator, since the value of bb^+ for fermions is non-vanishing only in the case when particles are absent.

After a T-transformation ($t \to -\, t'$), we represent the wave function in the form:

$$\psi' = b_\nu'(\boldsymbol{p}_\nu', s_\nu'^r)\, e^{-iE_\nu' t' + i(\boldsymbol{p}_\nu' \boldsymbol{r})} + b_{\bar{\nu}}'^{+}(\boldsymbol{p}_{\bar{\nu}}', s_{\bar{\nu}}'^r)\, e^{iE_{\bar{\nu}}' - t' - i(\boldsymbol{p}_{\bar{\nu}}' \boldsymbol{r})} \tag{7}$$

Comparing (7) and (6), we see that as a result of a T-transformation the creation operator of the antineutrino is converted into an annihilation operator of the neutrino ($b_{\bar{\nu}}^{+} \to b_\nu'$), and the momentum and helicity will be changed according to the law:

$$\boldsymbol{p} \to -\, \boldsymbol{p}', \qquad s_{\bar{\nu}}^r \to s_\nu'^r = -\, s_\nu^r, \qquad -s_{\bar{\nu}}^r \to s_\nu'^r = s_\nu^r \tag{8}†$$

i.e., the left-handed neutrino is converted into a right-handed one, which can be demonstrated by means of a mirror placed perpendicularly to the momentum (Fig. 11). We shall consider a change

† It can be shown by means of formulae (4) and (5) that as a result of all the transformations considered, even when the annihilation operators may be changed into creation operators, and the neutrino operators may be changed into antineutrino operators, the helicity belonging to a given operator remains unchanged, i.e.,

$$s'^r = -\, s'^l = s^r = \text{const.}$$

in helicity of the neutrino as non-invariance of theory relative to strong time reversal (symbolically $T \neq$ const).

As a result of a C-transformation, the sign of the lepton charge is changed, i.e., in place of (6) we have

$$\psi' = b'_{\bar{\nu}}(p'_{\bar{\nu}}, s'^{r}_{\bar{\nu}})\, e^{-iE_{\nu}'t + i(p_{\nu}'r)} + b'^{+}_{\nu}(p'_{\nu}, s'^{r}_{\nu})\, e^{iE_{\nu}'t - i(p_{\nu}'r)} \tag{9}$$

Comparing (9) and (6) we can see that as a result of a C-transformation the creation operator of the antineutrino is converted into a creation operator of the neutrino. For the momentum and helicity, we have

$$p \to p', \qquad s^{r}_{\bar{\nu}} \to s'^{r}_{\nu} = -\, s^{r}_{\nu}, \qquad s^{r}_{\bar{\nu}} \to s'^{r}_{\nu} = -\, s^{r}_{\nu} \tag{10}$$

i.e., the left-handed neutrino is converted into a right-handed neutrino (symbolically $C \neq$ const). A charge conjugate transformation for the neutrino can also be demonstrated by means of a mirror, but in the given case it should be placed parallel (Fig. 11) and not perpendicular to the momentum, as in the case of a T-transformation.

The joint ($TC = T'$)-transformation (i.e., weak time reversal) survives the theory of invariance. In this case, as one sees easily from equations (6), (7) and (9), the creation operator of the antineutrino is converted into the annihilation operator of the same antineutrino, and for the new momenta and helicities we shall have:

$$p \to -\, p', \qquad s^{r}_{\nu} \to s'^{r}_{\nu}, \qquad s^{r}_{\nu} \to -\, s'^{r}_{\nu} \tag{11}$$

Hence it can be seen that weak time reversal is equivalent to double mirror reflection (see Fig. 11), as a result of which the left-handed neutrino remains left-handed.

Finally, as a result of space inversion ($r \to -\, r$) the antineutrino creation operator remains the same antineutrino creation operator, but the momentum and helicity are changed according to the well-known rule of algebraic vectors:

$$p \to -\, p', \qquad s^{r}_{\nu} \to -\, s^{l}_{\nu}, \qquad s^{r}_{\nu} \to s^{l}_{\nu} \tag{12}$$

Hence it can be seen, that as a result of a P-transformation, the left-handed neutrino remains left-handed. However, if we take as

the helicity characteristic the direction of the axial vector having a definite sense, then as a result of this only the mathematical form is changed for describing left-handedness.

In connection with this, we note that by means of a single mirror, it is possible to describe a P-transformation, as a result of

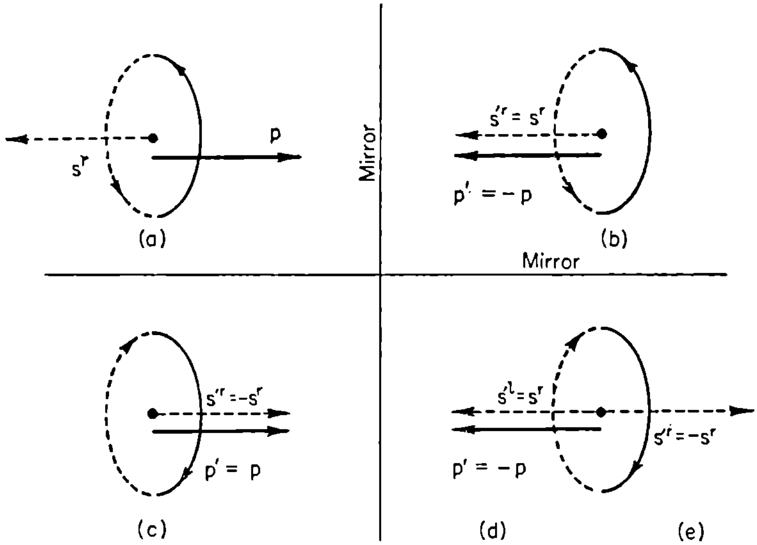

FIG. 11. *Representation of a change in helicity of the neutrino by means of a mirror (particles with positive energy) for T, C and P-transformations. (a) Original helicity, left-handed neutrino (right-handed system of coordinates); (b) T-transformation, right-handed neutrino (right-handed system of coordinates); (c) C-transformation, right-handed neutrino (right-handed system of coordinates); (d) P-transformation, left-handed neutrino (left-handed system of coordinates); (e) TC-transformation, left-handed neutrino (right-handed system of coordinates).*

the presence of either one of the parallel polar vectors (the mirror should be placed perpendicularly to these vectors), or one of the parallel axial vectors (the mirror should be placed parallel to these vectors).

As a result of the presence of parallel polar and axial vectors (i.e., helicity), a P-transformation, and likewise a CT-transformation, can be described by means of two reflections (see Fig. 11).

Let us pass on to the analysis of another possible asymmetry

relative to a C-transformation, which is the consequence not of the neutrino polarisation as in the previous case, but of the fact that the G_j coefficients for four-fermion interaction coupling are complex.

In this case, the binding energy has the form

$$U = \sum_j G_j(\psi_p^+ \gamma_j \psi_n)(\psi_e^+ \gamma_j \psi_\nu)$$

and

$$U^+ = \sum_j G_j^+(\psi_n^+ \gamma_j \psi_p)(\psi_\nu^+ \gamma_j \psi_e) \tag{13}$$

where ψ_p^+ is the wave function of the proton, ψ_n is the wave function of the neutron, etc., and the γ_j are the Dirac matrices defining the nature of the interaction.

In particular, in the case of combined vector ($G_j = G_V$, $\gamma_j = I$) and pseudovector ($G_j = G_A$, $\gamma_j = \sigma$) coupling, the four-fermion interaction (13) remains scalar, since it represents the scalar product of a vector and a vector and of a pseudovector and a pseudovector, and at the same time according to the two-component theory, the energy of interaction is the sum of a scalar and a pseudoscalar.

We shall now examine which particular effects are influenced by these two asymmetry phenomena as a result of a C-transformation.

In order to take into account the polarisation of the particles, it is necessary that the wave function should satisfy not only Dirac's equation (3) but also the supplementary condition (4). Two polarised states ($s = \pm 1$) are possible for the proton, the neutron, the positron, and the electron, but for the neutrino, the mass of which is equal to zero, there is only one possible state, so that for the neutrino $s_\nu^r = - s_\nu^l = -1$, and for the antineutrino $s_{\bar{\nu}}^r = - s_{\bar{\nu}}^l = 1$.

The decay probability for the neutron is proportional to the matrix element:

$$R_{n \to p + e^- + \bar{\nu}} = U^+ U \tag{14}$$

and for the antineutrino—to the matrix element:

$$R_{\bar{n} \to \bar{p} + e^+ + \nu} = UU^+ \tag{15}$$

In the case when the neutron decays with oriented spin, taking the polarisation properties of the neutrino into account gives the following formula for describing the asymmetry of the number of electrons emitted:

$$R = \text{const}\,(1-\beta a s_n s^{\bar{\nu}}(p_n^0 \cdot p_e^0)) \tag{16}$$

where

$$a = \frac{2G_A^+ G_A + G_V^+ G_A + G_A^+ G_V}{G_V^+ G_V + 3G_A^+ G_A} \tag{17}$$

where $c\beta$ is the velocity of the emitted electrons, and where $\boldsymbol{p}_e^0$ and $\boldsymbol{p}_n^0$ are the unit momentum vectors of the electron and neutron. For the neutron at rest, the direction of $\boldsymbol{p}_n^0$ should be chosen such that it forms a right-handed screw with its circular polarisation.

Then, as a result of the decay of a free neutron, we can put $s_n s_{\bar{\nu}} = 1$ in the right-handed system as well as in the left-handed system of coordinates. This asymmetry phenomenon, and similarly other phenomena which followed from the theory of non-conservation of parity, were verified by a number of precision experiments (Wu, Telegdi, Lederman *et al.*), whereby the value of 0·11 was established for the quantity a.

Hence, in the case when the G-components are real, it follows that

$$G_A = -\ 1{\cdot}2\, G_V$$

Having determined experimentally the half-life of the neutron (11·7 min), the numerical value of the G_V coefficient can be calculated:

$$G_V = (1{\cdot}42 \pm 0{\cdot}03)10^{-49}\,\text{erg}\,\text{cm}^3$$

In particular, it can be seen from formula (16) that in the direction which is right-handed with respect to the circularly polarised neutron, fewer electrons are emitted than in the opposite direction. By determining the decay of the antineutron, the matrix element (15) also leads to the formula of the form (16) and (17), if we substitute the latter

$$G \to G^+, \qquad s_{\bar{\nu}} \to s_\nu, \qquad s_n \to s_{\bar{n}} \tag{18}$$

This substitution, obviously, does not change the numerical value of the coefficient a (see (17)), but gives the other sign for the product $s_{\bar{n}} s_\nu$, since the neutrino has a helicity opposite to that of the antineutrino †:

$$s_\nu = - s_{\bar{\nu}}$$

Hence it follows, that as a result of the decay of an antineutron we shall have asymmetry but of opposite sense from the asymmetry observed with decay of the neutron, i.e., in the direction which is right-handed to the circularly-polarised antineutrino, a greater

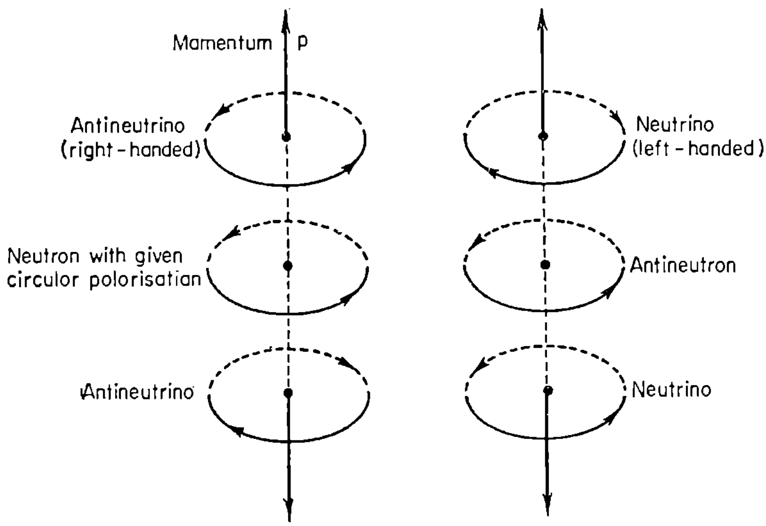

FIG. 12. *Origin of space and charge asymmetry as a result of the decay of a neutron and of an antineutron.*

number of positrons will be emitted. We recall that as a result of decay of a neutron, the least number of electrons were emitted in this direction.

The geometrical origin of space asymmetry, dependent on the helicity of the neutrino, is depicted in Fig. 12. Since the helicity

† Positron decay is also possible in the atomic nucleus ($p \rightarrow n + e^+ + \nu$). Then from expression (15), in order to transfer from the formula for nuclear electron beta-decay to the formula for positron decay, which also has the same form as (16) and (17), we must substitute in the latter

$$G_V \rightarrow G_V^+;\ G_A \rightarrow - G_A^+;\ s_{\bar{\nu}} \rightarrow s_\nu,\ s_n \rightarrow s_p.$$

is described there by a rotation (and not by an axial spin vector), then the asymmetry will have one and the same form in the right-handed as well as in the left-handed system of coordinates, i.e., the circular polarisation as a result of a P-transformation conserves its orientation relative to the momentum.

If the neutron is non-polarised, then non-conservation of parity (due to the helicity of the neutrino) should lead to a polarisation of the electrons, the extent of which is characterised by the formula:

$$R = \text{const}\,(1 - s_e s_{\bar{\nu}} \beta) \tag{19}$$

Hence it can be seen, that left-handed electrons will be mainly formed ($s_e s_{\bar{\nu}} = -1$) in both the left-handed and in the right-handed system of coordinates, since the antineutrino is right-handed ($s^r_{\bar{\nu}} = -s^l_{\bar{\nu}} = 1$). As a result of the decay of the anti-neutron, left-handed positrons will be mainly ejected, since the substitution $s_e s_{\bar{\nu}} \to s_{\bar{e}} s_\nu$ should be made in equation (19) and we should put $s^r_\nu = -s^l_\nu = -1$. In the ultra-relativistic case ($\beta = 1$), the extent of electron and positron polarisation should tend, obviously, towards 100%.

If the G-coefficients are complex, then even a third phenomenon of non-conservation of parity is possible, which is related to the new charge asymmetry, which is introduced by the complex values of the G-coefficients in the matrix elements (14) and (15).

As a result of investigating the decay of a polarised neutron, we find that the complex G-coefficients give an azimuthal asymmetry, the maximum of which lies in a plane perpendicular to the spin of the neutron $\left(\theta = \dfrac{\pi}{2}\right)$, when the polar asymmetry (see (16)), in general, vanishes.

As a result of neutron decay, this azimuthal asymmetry will be characterised by the following additional term:

$$\Delta R = \text{const}\, i(G_V^+ G_A - G_A^+ G_V)(s_n . [p^0_{\bar{\nu}} \wedge p^0_e]) \tag{20}$$

For an experimental detection of the azimuthal asymmetry, it is necessary to install two counters in a plane perpendicular to the

spin of the neutron, in order to register the momenta of the simultaneously appearing electron and antineutrino; experimentally it is much simpler to determine the momentum, not of the antineutrino, but of the proton

$$p_p = - p_e - p_{\bar{\nu}}$$

The phenomenon of azimuthal asymmetry is related geometrically to the different orientations of the two loops, just as in the case of polar asymmetry (see (16)). One of these loops characterises the longitudinal polarisation of the neutron (axial vector s_n) and the second one characterises the vector product of the momentum of the antineutrino $p_{\bar{\nu}}$ and that of the electron p_e, whereby the direction of the latter loop is defined by the direction of the first vector p_ν (axial vector $[p^0_{\bar{\nu}} \wedge p^0_{\bar{e}}]$).

The presence of the asymmetry term ΔR, expressing the complexity of the G coupling constants for a four-fermion interaction, can be observed experimentally if the spin of the neutron is turned through an angle of 180°. In this case, the mutual orientation of the loops is changed to the opposite sense, which should lead to a change of sign of the ΔR term (Fig. 13).

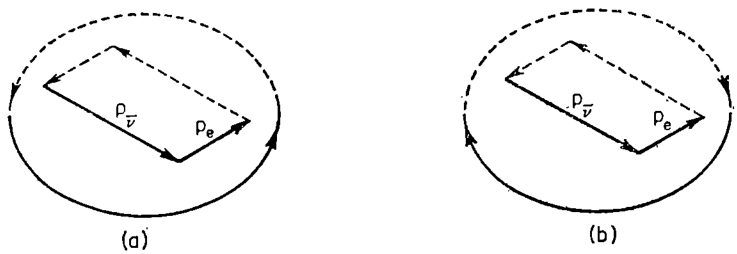

FIG. 13. *Change of azimuthal symmetry as a result of inverting the spin of the neutron; (a) is the circular polarisation of the neutron prior to spin inversion; (b) is the circular polarisation after spin inversion.*

Experiments, associated with the detection of this third correlation, need to be of an extremely precise nature and therefore even up to now the existence of this term is not accurately shown, although earlier experiments indicate its absence, i.e., the reality of the G-coefficients.

In the case of antineutron decay we should, according to (18), make the substitution $G \to G^+$, $s_n \to s_{\bar{n}}$, etc., in expression (20), which changes the sign of the ΔR term, i.e., expression (20) is not invariant relative to a C-transformation.

However, we shall show that in the theory of neutron polarisation, the results obtained should always conserve invariance relative to those transformations which convert the neutrino operator once again into a neutrino operator.†

Space inversion should be one of the number of free transformations:

$$G \to G, \qquad p \to -p, \qquad s^r \to s^l \tag{21}$$

and also the transformation of weak time reversal $T' = CT$:

$$G \to G^+, \qquad p \to -p, \qquad s^r \to -s^r \tag{22}$$

It is easy to verify that all three actual results (see (16), (19) and (20)) which characterise non-conservation of parity are invariant relative to P and T'-transformation. Consequently, a generalisation of the CPT-Theorem in the case of the polarised neutron can be represented in the form:

$$PT' = CPT = \text{const} \tag{23}$$

As a result of analysing non-conservation of parity by means of the combined inversion of Landau, Lee and Yang in the case of complexity of the G-coefficients, the CPT-Theorem leads to certain contradictory results. Actually, non-conservation of parity, associated with complexity of the G-coefficients (see (20)), gives the relation (23). At the same time, the phenomenon of non-conservation of parity, due to taking into account the polarising properties of the neutrino (see (16) and (19)), should lead to a combined inversion of the form:

$$P \neq \text{const}, \qquad C \neq \text{const}, \qquad PC = \text{const}, \qquad T' = \text{const} \tag{24}$$

because of which the generalisation of the CPT-Theorem in the

† We note that as a result of one C- or one T-transformation, the neutrino operator is changed into the antineutrino operator.

presence of helicity looks like taking the form

$$CPT' = \text{const} \tag{25}$$

Since the transformation (23) contradicts transformation (25), advocates of the combined inversion assume that expression (20) should be equated to zero, or as they say, there should be no time non-invariance. This is possible only in the case when all the G-coefficients are real.

According to the polarised neutrino theory, all three formulae (16), (19), and (20) are a consequence of the non-invariance of the theory relative to a C-transformation,† i.e., a transition from particle to antiparticle, and they remain invariant as a result of a P-transformation and also as a result of a T'-transformation. Consequently, in accordance with the latter point of view, the G-coefficients can be complex as well as real. Actually, the introduction of neutrino polarisation, and also of the complexity of the G-coefficients, will satisfy one and the same condition (23). The absence of the supplementary term (20) does not contradict the theory and will have an effect only on the reality of the G-coefficients.

It is possible that in the course of time we shall succeed in finding asymmetry phenomena associated with complex G-coefficients.

It should be emphasised that the discovery of the phenomenon of non-conservation of parity has permitted not only a qualitative but also a quantitative explanation of beta-disintegration and meson decay, although many problems associated with weak interactions still remain unexplained.

† This leads automatically to the non-invariance of the theory relative to a T-transformation.

6

"Abandoned and Strange" Particles; "Resonons"

It is well known that Yukawa predicted the existence of quanta from the nuclear field, which were later called pions. However, the situation as to an experimental detection of these particles was complicated, due to the fact that muons were detected first, which were erroneously taken to be quanta from the nuclear field. In making this incorrect assumption, it was found, for instance, that the mass of the muon was indicated to be 207 m_0, i.e., in agreement with Yukawa's prediction. However, muons could not pretend to be nuclear field quanta, since they did not show a strong interaction with nucleons. Actually, their spin was shown to be one-half, and consequently they, just like electrons, could not be absorbed or ejected by the nucleus without participation of a neutrino.

Now that the real nuclear field quanta (pions) have been discovered, the existence of muons still cannot, as yet, be justified. Consequently, the theoreticians call them in fun "abandoned" particles. The muon has a relatively large lifetime (10^{-6} sec), since it decays into three particles: an electron (positron), and two antineutrinos (neutrinos). Since muons are similar to electrons in their properties (spin, charge, nuclear inactivity), they may form mu-mesic atoms, where the principal role is played by electrical forces, just as in the normal atom. Around the nucleus of

a mesic atom, negative muons rotate in place of electrons. Since the mass of the muon is more than 200 times greater than the mass of the electron, the radius of the mu-mesic atom will be 200 Z times less than the atom of hydrogen, where Z is the atomic number of the element.

The study of the heavy mu-mesic atoms (with high Z) presented particular interest. Their orbital radius lies within the nucleus, which made it possible to determine more accurately many data concerning the distribution of charge in the nucleus.

In determining the lepton charge of μ-mesons, we shall take into account the following experimental facts: (a) as a result of the decay of a π^--meson, right-handed neutrinos (or anti-neutrinos) are formed together with a right-handed μ^--meson; (b) the right-handed muon–neutrinos are not identical with the right-handed electron–antineutrinos (as a result of absorption by nucleons of the fast muon–neutrinos, only μ-mesons and no electrons are formed).

These facts can be satisfied if we use a four-component theory for describing the neutrino, which gives two types of solution (see footnote on page 41). If the first type of solution (the neutrino ν is left-handed, and the antineutrino $\bar{\nu}$ is right-handed) refers to the electron–neutrino, then the second type of solution (neutrino ν' is right-handed, and the antineutrino $\bar{\nu}'$ is left-handed) should refer to the muon–neutrino.

In this case, decay of π-mesons will take place according to the scheme

$$\pi^- \rightarrow \mu^- + \nu'$$

$$\pi^+ \rightarrow \mu^+ + \bar{\nu}'$$

whereby on the strength of the fact that the μ-meson and the neutrino are shot off in opposite directions, the helicity of μ-mesons should coincide with the helicity of the neutrino.

Hence, it can be seen that the lepton charge of the μ^+-meson, just like the electron, is equal to plus unity, and that of the μ^--meson is equal to minus unity. Because of this, in particular,

the decay

$$\mu^- \to e^- + \gamma$$

is forbidden.

Thus, the discovery of the muon–neutrino is naturally wrapped up in the framework of the four-component theory and restricts the applicability of the two-component theory of Lee, Yang and Landau.

The next, extremely important step in the development of the science of the elementary particles was the discovery of the strange particles (K-mesons and hyperons).

The strangeness of their behaviour is manifested in the fact that their decay process takes place according to one reaction, and their process of formation takes place according to another.†

Thus, for example, the lambda-hyperon (Λ is a neutral particle), under the action of weak interactions (with a lifetime of 10^{-10} sec) decays into a proton (p) and a π^--meson. Conversely, as a result of the collision of a proton and a negative pion, a single lambda-hyperon cannot be formed, i.e., the process of decay of the strange particles and the process of their formation is non-reversible. A lambda-hyperon is always formed together with another strange particle, for example a K^0-meson, in which the process of formation is characterised by a time of the order of 10^{-23} sec, i.e., it depends on strong interactions. Thus, the strange particles are always born jointly, in pairs (strong interactions), and decay one at a time.

In order to explain the creation processes, a new characteristic

† It is well known that the characteristic time of different processes is proportional to the square of the corresponding interaction constant. If we denote the squares of the constants of strong, electromagnetic and weak interactions by g^2, e^2 and f^2, we have for their ratios the following values: $g^2 : e^2 : f^2 = 1 : 10^{-3} : 10^{-15}$. Therefore, if the time for the transformation of the elementary particles as a result of strong interaction (for example, absorption of pions by a proton) is of the order of 10^{-23} sec, then the reaction time as a result of electromagnetic interaction will be, as a rule, approximately 1,000 times greater. The characteristic time for reactions governed by weak interactions (for example, decay of a pion) will be of the order 10^{-8} to 10^{-10} sec.

of the elementary particles was introduced, called the "strangeness", which is denoted by the symbol S.

This quantity should be conserved in processes governed by strong interactions, for example, as a result of the formation of hyperons.

In order to explain the reaction

$$p+\pi^- = \Lambda + K^0$$

originating by the action of a strong interaction so that $\sum S = \text{const}$, it was necessary to put the strangeness of the K^0-meson equal to plus unity ($S = +1$), and that of the lambda-hyperon equal to minus unity ($S = -1$). As a result of the decay of these strange particles (weak interactions), the strangeness may be changed by unity ($S = \pm 1$); for example, in the decay reaction $\Lambda \rightarrow p + \pi^-$ the strangeness of the lambda-hyperon is equal to minus unity, and for the proton and for the pion it is equal to zero.

The experimental discovery of a hyper-nucleus in which, for example, one of the neutrons is replaced by a lambda-hyperon was shown to be extremely important in the study of hyperons. The system $p+\Lambda$ (i.e., a lambda-deuteron ${}_{\Lambda}H^2$) does not exist. This indicates that the forces of interaction between p and Λ are somewhat weaker than between p and n, but they are of the same order, since the following hyper-nuclei can be formed:

$${}_{\Lambda}H^3(p+n+\Lambda), \qquad {}_{\Lambda}H^4(p+2n+\Lambda)$$

etc., up to the heaviest. The lifetime of the hyper-nucleus coincides approximately with the lifetime of the lambda-hyperon (10^{-10} sec).

The existence of hyper-nuclei once again emphasises the generality of nucleons and hyperons and justifies their inclusion in a single group of baryons with identical baryon number $B = 1$.

Gell-Mann, and Nishijima, independently of him, in 1955 suggested that the classification of the strongly interacting particles (pions, nucleons, strange particles) should be carried out by means

of the following formula:

$$Q = I_3 + \frac{B+S}{2}$$

where Q is the electrical charge of the particle, expressed in units of e_0, I_3 is the third component of the isotopic spin, B is the baryon number and S is the strangeness.

For the first group of bosons, namely pions, $S = 0$ and $I = 1$. Consequently, we have for them a charged triplet, such that the value of the electrical charge coincides with the isotopic spin component:

$$Q = I_3$$

since $I_3 = +1$, 0 or -1 for π^+, π^0 and π^--mesons respectively.

The decay of charged pions takes place as a result of strong interactions, and therefore the lifetime is of the order 10^{-8} sec. The neutral meson decays as a result of electromagnetic interactions $\pi^0 \rightarrow 2\gamma$ and therefore its lifetime is considerably less (10^{-16} sec).

For the second group of bosons, the K-mesons, $I_3 = \pm \frac{1}{2}$ (doublets) should be substituted in the Gell-Mann and Nishijima formula, and $B = 0$, $S = \pm 1$. Therefore, four K-mesons should exist.

For the K^+-meson:

$$S = 1 \text{ and } I_3 = \tfrac{1}{2}$$

for the K^0-meson:

$$S = 1 \text{ and } I_3 = -\tfrac{1}{2}$$

In the case where

$$S = -1 \text{ and } I_3 = \pm \tfrac{1}{2}$$

we shall have the corresponding antiparticles

$$\overline{K^0} \text{ and } \overline{K^-}$$

If the $\overline{K^-}$-antimeson differs from the K^+-meson not only in strangeness, but also in sign of the electrical charge, then the $\overline{K^0}$-antimeson will differ from the K^0-meson only in strangeness, which is very relevant during the creation of these particles, when strangeness should be conserved.

The K^+-meson can decay into two as well as three pions. For a long time it was assumed that these were different particles. The first was called a tau-meson (τ) and the second a theta-meson (θ). Nowadays, we know that this is one and the same type of particle.

The problem of solving the "tau–theta" riddle was incorporated originally in the work on non-conservation of parity; however, up to the present this riddle has still not been finally solved.

Similarly two neutral K-mesons (K^0 and $\overline{K^0}$) can exist only in a definite mixture with one another, containing these and other particles in equal proportions.

The superposition of these neutral mesons forms in turn two states, the K_1^0-meson and the K_2^0-meson, so that the existence of the K_2^0-meson was predicted on the basis of the scheme for the strange particles.

The primary difference between these neutral mesons consists in their modes of decay. The K_1^0-meson decays into two pions with a lifetime of 10^{-10} sec, and the K_2^0-meson decays into three pions with a lifetime of 10^{-7} sec. In this respect, the K_1^0-meson reminds us to a certain extent of the parapositron (decaying into 2γ), and the K_2^0-meson reminds us of the orthopositron (decaying into 3γ).

Thus, the neutral K-mesons differ in one aspect when created at birth, and in another aspect when decaying.

If the division into particles and antiparticles in the group of bosons is not of a sharp nature, since $B = 0$, then the division into particles and antiparticles in the group of fermions (baryons) is closely limited, and it is characterised by the different value of the baryon number B (for particles $B = 1$; for antiparticles $B = -1$).

All the particles of the baryon group can be obtained from the Gell-Mann and Nishijima formula.

For nucleons, $I = \frac{1}{2}$ (doublets) and $S = 0$. Altogether there will be two pairs of doublets with $B = 1$ (nucleons) and $B = -1$ (antinucleons).

For hyperons, we have the following possibilities:

(a) A pair of neutral singlets ($I = 0$), differing from each other in the value of the strangeness and nucleon charge: for lambda-hyperons $B = 1$, $S = -1$; for anti-lambda-hyperons $B = -1$, $S = 1$.

(b) A pair of triplets ($I = 1$, $B = 1$, $S = -1$ for one triplet, and $I = 1$, $B = -1$, $S = 1$ for the other triplet), combining in a single species the so-called sigma-hyperons, and

(c) A pair of doublets ($I = \frac{1}{2}$, $B = 1$, $S = -2$ and $I = \frac{1}{2}$, $B = -1$, $S = 2$), forming the so-called cascade xi-hyperons.

Since the strangeness of the xi-hyperons is equal to minus two, then they may be created as a result of the collision of a proton with a negative K-meson, the strangeness of which is already equal to minus one:

$$\overline{K^{-}} + p \rightarrow \begin{cases} \Xi^{-} + K^{+} \\ \Xi^{0} + K^{0} \end{cases}$$

In this reaction, the law of conservation of strangeness (strong interactions) should hold in addition to conservation of baryon number.

Since the strangeness is changed by unity as a result of decay of the strange particles, the xi-hyperon is transformed into a nucleon in two stages (i.e., through an intermediate cascade):

$$\Xi^{-} \rightarrow \Lambda + \pi^{-} \rightarrow p + 2\pi^{-}$$

Thus, the introduction of strangeness and of baryon number makes it possible to classify strongly interacting particles. This classification, given by Gell-Mann and Nishijima is presented in Table Two.

Having determined the strangeness S, it is possible to find the charge multiplicity and the greatest number of particles forming the given species. Of course, for this it is further necessary to take into account that antiparticles should exist together with the particles, and which are not only oppositely charged, but also have the opposite baryon number and strangeness. Thus, Gell-

TABLE TWO

Strongly Interacting Particles, according to Gell-Mann and Nishijima

Strangeness S Particles	*Strangeness S* Anti-particles	*Charge multiplicity*	$Q = 1$	$Q = 0$	$Q = -1$	$Q = 0$	$Q = 1$	$Q = 0$	$Q = -1$
						Bosons $B = 0$			
0	0	Singlet $I = 0$				** π_0^0			
		I_3				0			
0	0	Triplet $I = 1$			π^-	π^0	π^+		
		I_3			-1	0	$+1$		
1	-1	Doublets $I = 1/2$	K^+	K^0				* $\overline{K^0}$	$\overline{K^-}$
		I_3	1/2	$-1/2$				1/2	$-1/2$
				Baryon $B = 1$				Antibaryon $B = -1$	
0	0	Doublets $I = 1/2$	p	n				*$\bar{n}$	*$\bar{p}$
		I_3	1/2	$-1/2$				1/2	$-1/2$
-1	1	Singlets $I = 0$		Λ				* $\bar{\Lambda}$	
		I_3		0				0	
-1	1	Triplets $I = 1$	Σ^+	* Σ^0	Σ^-		* $\overline{\Sigma^+}$	* $\overline{\Sigma^0}$	* $\overline{\Sigma^-}$
		I_3	1	0	-1		1	0	-1
-2	2	Doublets $I = 1/2$		* Ξ^0	Ξ^-		* $\overline{\Xi^+}$	** $\overline{\Xi^0}$	
		I_3		1/2	$-1/2$		1/2	$-1/2$	

The formula $Q = I_3 + (B+S)/2$ is the basis for the classification, where Q is the electrical charge (in units of e_0), I is the isospin, I_3 is the isospin component, B is the baryon number, S is the strangeness.

The elementary particles whose existence was predicted by theory are indicated by asterisks; such that one asterisk denotes that the particle was subsequently detected experimentally after prediction, and two asterisks signify that the particle has not yet been detected.

Mann and Nishijima predicted the series of particles which are presented in Table Two.

The existence of the as yet undiscovered anti-xi-zero-hyperon gives no cause for doubt. Moreover, the value of its principal characteristics can be predicted accurately: mass, charge, strangeness, etc.

The problem of the singlet-boson, the so-called π_0^0-meson, the existence of which does not contradict Gell-Mann and Nishijima's Table, is still far from being explained.

The Gell-Mann and Nishijima Table does not show the light fermions (electrons, muons, neutrino, etc.) and the photon, which we have placed in Table Three.

In order to characterise the light particles, it is not necessary to introduce isotopic spin, strangeness and baryon number, which determines the position of the particle in the Gell-Mann and Nishijima system, and therefore the light particles are best not included in this scheme. On the other hand, besides electrical charge, they are characterised further by their leptonic charge, which for strongly interacting particles is equal to zero.

All the elementary particles which have so far been discovered (or have been predicted with certainty) are presented in Table Four.

Obviously, one boson should further exist, namely the graviton, which should also be included in a future more general scheme of elementary particles. According to D. D. Ivanenko's theory, gravitons can be transformed into electron–positron, neutrino–antineutrino pairs and other particles. The experimental existence of gravitons will be conclusively indicated if gravitational waves are detected. Thus, the problem of detection of gravitational waves has already been placed on the agenda and it presents one of the most important problems of modern times.†

One of the main problems is the creation of a general theory for elementary particles, in particular to further improve the

† It is possible that the gravitational field plays a significant role in determining the internal properties of elementary particles.

TABLE THREE

Light Elementary Particles (Leptons)

Interaction	*Muonic*	*Electronic*		*Electronic*	*Muonic*
Leptonic charge →	+1 particles		0	−1 antiparticles	
Photons			γ		
Neutrinos	ν' (right-handed)	ν (left-handed)		$\bar{\nu}$ (right-handed)	$\bar{\nu}'$ (left-handed)
Electrons		e^-		e^+	
Muons	μ^+				μ^-

TABLE FOUR

Elementary Particles

Class and spin	Symbol	Sign of charge	Name	Mass MeV	Mass m_0	Reaction of formation	Mode of decay	Lifetime sec.
Boson $s = 1$	γ	0	Photon	0	0		Stable	∞
Leptons $s = 1/2$	ν, ν'	0	Neutrino	0	0		Stable	∞
	$\bar{\nu}, \bar{\nu}'$	0	Antineutrino					
	e^-	−	Electron	0·51	1	$\gamma + \gamma \rightarrow e^+ + e^-$	Stable	∞
	e^+	+	Positron					
	μ^-	−	Mu-minus	106	207		$\mu^- \rightarrow e^- + \bar{\nu}' + \bar{\nu}$	$2{\cdot}2 \times 10^{-6}$
	μ^+	+	Mu-plus †					
Bosons $s = 0$ *Mesons*	π^0	0	Pi-zero	135	264	$p + p \rightarrow \begin{cases} p + n + \pi^+ \\ p + p + \pi^0 \end{cases}$	$\pi^0 \rightarrow \gamma + \gamma$	$2{\cdot}3 \times 10^{-16}$
	π^-	−	Pi-minus	140	273	$p + \bar{p} \rightarrow 5\pi$	$\pi^- \rightarrow \mu^- + \nu'$	$2{\cdot}6 \times 10^{-8}$
	π^+	+	Pi-plus					
	K^+	+	*K*-plus	494	967		$K^+ \rightarrow \begin{cases} \pi^+ + \pi^+ + \pi^- \\ \pi^+ + \pi^0 \end{cases}$	$1{\cdot}2 \times 10^{-8}$
	$\overline{K^-}$	−	*K*-minus					
	K^0	0	*K*-zero (50% K_1^0)	498	974	$\pi^- + p \rightarrow K^- + K^0 + p$	$K_1^0 \rightarrow \pi^+ + \pi^-$	$1{\cdot}0 \times 10^{-10}$
	$\overline{K^0}$	0	Anti-*K*-zero (50% K_2^0)				$K_2^0 \rightarrow \pi^+ + \pi^- + \pi^0$	$0{\cdot}6 \times 10^{-7}$

Nucleons	p	+	Proton	938·2	1836·1		Stable	∞
	$\bar{p}$	−	Antiproton					
	n	0	Neutron	939·5	1838·6		$n \to p + e^- + \bar{\nu}$	$1{\cdot}0 \times 10^3$
	$\bar{n}$	0	Antineutron					
Baryons s = 1/2 *Hyperons*	Λ	0	Lambda	1115	2183	$\pi^+ + n \to \Lambda + K^+$	$\Lambda \to p + \pi^-$	$2{\cdot}5 \times 10^{-10}$
	$\bar{\Lambda}$	0	Anti-lambda			$\pi^+ + p \to \Sigma^+ + K^+$		
	Σ^+	+	Sigma-plus	1189	2328	$\pi^- + p \to \begin{cases} \Sigma^0 + K^0 \\ \Sigma^- + K^+ \end{cases}$	$\Sigma^+ \to p + \pi^0$	$0{\cdot}8 \times 10^{-10}$
	$\overline{\Sigma^-}$	−	Anti-sigma-plus					
	Σ^0	0	Sigma-zero	1192	2332		$\Sigma^0 \to \Lambda + \gamma$	$\begin{cases} <10^{-11} \text{ exp.} \\ 10^{-19} \text{ theor.} \end{cases}$
	$\overline{\Sigma^0}$	0	Anti-sigma-zero					
	Σ^-	−	Sigma-minus	1196	2341		$\Sigma^- \to n + \pi^-$	$1{\cdot}6 \times 10^{-10}$
	$\overline{\Sigma^+}$	+	Anti-sigma-minus					
Cascade hyperons	Ξ^0	0	Xi-zero	1311	2566	$K^- + p \to \begin{cases} \Xi^0 + K^0 \\ \Xi^- + K^+ \end{cases}$	$\Xi^0 \to \Lambda + \pi^0$	$1{\cdot}5 \times 10^{-10}$
	$\overline{\Xi^0}$	0	Anti-xi-zero ‡				$\Xi^- \to \Lambda + \pi^-$	$1{\cdot}3 \times 10^{-10}$
	Ξ^-	−	Xi-minus	1318	2580			
	$\overline{\Xi^+}$	+	Anti-xi-minus					

† We do not introduce here the mode of decay of antiparticles. In order to convert the decay scheme of particles into the decay scheme of antiparticles, we must replace all particles by the corresponding antiparticles.

‡ This particle has not yet been detected experimentally.

development of the theory of strong interactions, where obviously the individual particles are strongly associated with the vacuum.

Indeed, if the vacuum magnetic moment of the electron is approximately one thousandth less than the Dirac value, then for the proton it is found to be approximately a factor of two greater than the Dirac value.

In analysing the experiments of Hofstadter and Wilson on the scattering of fast electrons by nucleons, we came to the conclusion that the pions surrounding the nucleon are found in such an excited state, that the pion cloud represents something between the actual state reminiscent of the electrons in the atom, and the virtual state dependent upon, for example, the polarisation of the vacuum.

Considerable interest in the development of all these problems is also aroused by the recently discovered resonance states in a system of strongly interacting particles ("resonons") in the region of high energies (several hundred mega-electron volts), which form some short-lived metastable combinations.

"Resonons" were discovered during investigations into the interaction of ultra high energy particles obtained, as a rule, in accelerators.

We had already observed similar "resonons" in the scattering of pions by nucleons (see Figs. 7 and 8), where they appeared in the form of peaks. These resonances may be associated with nucleon "resonons". Apart from nucleon "resonons", "pi-resonons", "K-resonons" and "hyperon resonons" have been discovered recently. The principal resonons are presented in Table Five, where a few possible modes of formation and of decay are also given.

"Resonons" cannot be considered as new elementary particles, since they have a relatively large resonance width. In exactly the same way, their positive energy of interaction does not warrant their consideration as atom-like combinations. Obviously, they represent some form of combination of elementary particles.

It should also be emphasised that in the past many attempts

TABLE FIVE

Principal Resonons †‡

Name	*Symbol*	*Isospin*	*Spin*	*Mass MeV*	*Resonance width*	*Possible mode of formation*	*Possible mode of decay*
Pi-resonons	ρ	1	1	760	50	$\pi + N \rightarrow N + \rho$	$\rho \rightarrow 2\pi$
$S = 0$	ω	0	1	790	12	$\bar{N} + N \rightarrow \omega + 2\pi$	$\omega \rightarrow 3\pi$
$B = 0$	η	0	0	550	8	$\pi^+ + {}^2H \rightarrow \omega + 2p$	$\eta \rightarrow 3\pi$
						$\pi^+ + {}^2H \rightarrow \eta + 2p$	$\eta \rightarrow 2\gamma$
K-resonons							
$S = 1$	K^*	1/2	1	885	30	$K + N \rightarrow K^* + N$	$K^* \rightarrow K + \pi$
$B = 0$							
Nucleon	N^*	3/2	3/2	1238	75	$\gamma + N \rightarrow N^*$	$N^* \rightarrow N + \pi$
resonons	N^{**}	1/2	3/2	1516	60	$\pi + N \rightarrow N^*$	
$S = 0$	N^{***}	1/2	5/2	1683	70		
$B = 1$	N^{****}	3/2	3/2	1900	100		
Hyperon	Y_1^*	1	3/2	1385	25	$\bar{K} + N \rightarrow Y_1^* + \pi$	$Y_1^* \rightarrow \Lambda + \pi$
resonons	Y_0^*	0	1/2	1405	20		$Y_0^* \rightarrow \Sigma + \pi$
$S = -1$	Y_0^{**}	0	3/2	1520	8		$Y_0^* \rightarrow \Lambda + \pi$
$B = 1$	Y_0^{***}	0	Half-odd-integral	1815	60		$Y_0^* \rightarrow \Lambda + 2\pi$

† The masses shown are in the centre of mass system. Here N is a nucleon, i.e., a proton or neutron, and $\bar{N}$ is an antinucleon. The lifetime of the "resonons" is equal to 10^{-20} to 10^{-22} sec, i.e., it is much less than the lifetime of the elementary particles. Nucleon "resonons" appear also in the form of peaks during scattering of mesons by nucleons. In particular, the resonance in the system where a proton is at rest, is equal to the kinetic energy of 180 MeV pions (see Figs. 7 and 8), corresponding (in the centre of mass system) to a total energy of 1238 MeV, i.e., an N^*-"resonon". The existence has been conclusively established of only those resonons for which a spin number is given.

‡ The data on resonons are changing practically from day to day, and it is impossible to keep them completely up to date. For a recent survey and critical discussion of these data, and one which is supposed to be brought up to date at least once a year, see M. Roos, *Rev. Mod. Phys.* **35**, 314 (1963).

have been made to consider certain elementary particles (especially bosons) as combinations of other so-called fundamental elementary particles. Thus, for example, at one time the neutrino theory of light was developed, according to which a photon is represented as the combination of a neutrino and an antineutrino.

Since we have little experimental data on the structure of leptons, the most recent investigations have been carried out primarily in accordance with the theory of the combination of strongly interacting particles. The most interesting development in this direction is Sakata's model, according to which all strongly interacting particles consist of nucleons (possessing Q and B) and lambda-hyperons (possessing B and S). Sakata introduced the hypothesis that between any of the fundamental baryons (p, n, Λ) and any of the fundamental antibaryons $(\bar{p}, \bar{n}, \bar{\Lambda})$ there exists an attraction at small distances ($\sim 10^{-14}$ cm), whilst at the same time a repulsive force should act between two fundamental baryons (or antibaryons). Having been attracted to one another, the baryons and antibaryons form pions or K-mesons.

Thus, the combination of a nucleon and an antinucleon can form a triplet species of pions:

$$\pi^+ = p\bar{n}, \qquad \pi^- = \bar{p}n, \qquad \pi^0 = \frac{1}{\sqrt{2}}(p\bar{p} - n\bar{n})$$

Further, the combination of a nucleon and an anti-lambda-hyperon (or antinucleon and lambda-hyperon) gives two doublet species of K-mesons:

$$(1)\ K^+ = p\bar{\Lambda}, \quad K^0 = n\bar{\Lambda}; \qquad (2)\ \bar{K^-} = \bar{p}\Lambda, \quad \bar{K^0} = \bar{n}\Lambda$$

According to this scheme, not only bosons but also sigma and xi-hyperons, which also belong to this scheme of strongly interacting particles, are complexes. Thus, for example, sigma-hyperons should consist of a nucleon, an antinucleon and a lambda-hyperon:

$$\Sigma^+ = p\bar{n}\Lambda, \qquad \Sigma^- = \bar{p}n\Lambda, \qquad \Sigma^0 = \frac{1}{\sqrt{2}}(p\bar{p} - n\bar{n})\Lambda, \text{ etc.}$$

Similarly,

$$\Xi^- = \bar{p}\Lambda\Lambda, \qquad \Xi^0 = \bar{n}\Lambda\Lambda, \text{ etc.}$$

One of the most important consequences of Sakata's model is the fact that together with the formation of the complex "long-lived" particles (lifetime 10^{-8} to 10^{-16} sec) already indicated and for which the mass should be less than the sum of the individual particle masses (since a large binding energy "eats up" part of the mass), the formation of "resonons" (quasi-particles) is also possible having a mass which exceeds the total mass of the individual particles, owing to the fact that they are only slightly stable and have a lifetime of the order 10^{-22} sec. It should be emphasised that Sakata's scheme is not entirely approved and is factually of a kinematic nature, since it does not define the physical nature of interaction of the elementary particles.

Consequently, the problem is put to the scientists of the creation of a theory of strong coupling, which first and foremost should give the mass spectrum of the elementary particles. It is possible that investigations of the mass spectrum would permit an explanation of a regular pattern of strongly interacting particles in the same way that an analysis of the optical spectra of atoms led in due course to quantum mechanics.

The establishment of the spectrum of the "resonons" (energy, spin, isospin, parity, etc.) is also one of the paramount problems in the theory of strong interactions.

The recently created dynamic quantum theory of strong coupling, which is as yet of a particularly preliminary nature, can be divided to a first approximation into field and phenomenological theories.

The non-linear wave equation of Ivanenko–Heisenberg should be mentioned first of all; from this certain qualitative results were obtained, for example, the mass spectrum of strongly interacting particles. Schwinger has also started to develop field methods of investigation. Considerable success was achieved by means of the usual dispersion relations (Goldberger, Bogolyubov *et al.*) and in particular by means of dual dispersion relations (Mandelstam,

Chew *et al.*). In the latter papers, which can be related rather to phenomenology, certain qualitative results were established from a number of general principles (causality, unitarity, etc.), without the introduction of any specific field interaction between the particles.†

Finally, extremely important results were obtained very recently in the theory of strong coupling, arising from Regge poles. Regge's theory represents the furthest development of potential scattering in ordinary quantum mechanics. In this theory, it is shown that in the theory of potential scattering, the pole can lie not only on the real axis, but also in the complex plane of the orbital angular momentum.

In particular, by applying this theory to strongly interacting particles, it can be shown that the formation of "resonons" should correspond to the case when the pole in the potential scattering lies in the complex plane of the orbital momentum.

Thus, there appeared to be certain foundations for having confidence that a theory of strong coupling will yet be built up in the near future. However, a generalisation of Regge theory to high energy pion–nucleon scattering does not give agreement with recent experimental data.

In analysing the progressive development of the science of elementary particles, it should be noted that although a number of new particles were discovered in cosmic rays—the positron (Anderson, 1932), muons (Neddermayer and Anderson, 1937), pions (Powell, 1947), certain K-mesons (Le Prince, Ringuet, O'Cealleigh *et al.*, 1942–1947), certain hyperons (Rochester and Butler, 1947), the principal investigations concerning elementary particles, however, were successfully carried out only after powerful accelerators had been built.

Thus, for example, in the proton accelerators the "Cosmotron"

† It is possible that by means of field theoretical methods, a number of conclusions obtained from dispersion relations may be successfully verified. In connection with this, we are putting great hopes on damping theory, where the principles of causality and unitarity are automatically fulfilled.

at 3·5 GeV, the "Bevatron" at 6·5 GeV (U.S.A.) and the 10 GeV synchrotron (Dubna, USSR), monochromatic beams of pions, *K*-mesons and hyperons were obtained, and new particles were discovered: antiprotons, antineutrons (Segré, Chamberlain *et al.*, 1955), families of hyperons and antihyperons. The recently commissioned accelerators (approximately 30 GeV) in Geneva (Switzerland) and Brookhaven (U.S.A.) have made it possible to obtain very intense beams of antiprotons. Information has just been received concerning the discovery in these powerful accelerators of the anti-xi-minus-hyperon, and also of the muon–neutrino (Lederman, Steinberger *et al.*), predicted by B. M. Pontecorvo. Nowadays, in the USSR we are constructing even more powerful proton accelerators with energies of the order of 70 GeV.

It is well known that scientists were able to observe more details of the universe only after the telescope was built. In the microworld, the accelerator can serve as a similar "telescope". The high speed beams consisting of charged particles can be used for bombarding other elementary particles, which give experimental data concerning their structure. The greater the power of the accelerator, the greater will be the detail "viewed" in the elementary particles.

It should be emphasised that in the development of the science of elementary particles electron accelerators should also play a special role. Actually, high-speed electrons, being nuclearly inactive particles, will penetrate nucleons relatively easily, and will give an insight into many details of their internal structure, which it is in no way possible to "view" by means of the more powerful proton accelerators.

In connection with this, we are reminded that in the currently operating relatively small electron accelerators with energies of the order of 1 GeV, the electromagnetic structure of the nucleon has already been disclosed (Hofstadter and Wilson's experiments). At present, Harvard University (U.S.A.) have entered into the construction of an electron accelerator with an energy of 6 GeV, which should help in the understanding of even finer details of

nucleon structure. In the construction of cyclic electron accelerators, the greater losses resulting from synchrotron radiation should be taken into account (D. D. Ivanenko and I. Ya. Pomeranchuk, L. A. Artsimovich, A. A. Sokolov), which are practically absent in proton accelerators. The maximum synchrotron radiation occurs at very high harmonics, owing to the fact that, as we have already indicated, it leads to radiation of an oscillatory nature at relatively high energies, which in turn lead to quantum excitation of betatron oscillations (A. A. Sokolov, I. M. Ternov, A. A. Kolomenskii *et al.*). These quantised oscillations were detected experimentally by F. A. Korolev (USSR) and also by M. Sands (U.S.A.). Owing to the synchrotron radiation, the construction of cyclic electron accelerators with energies in excess of a few GeV creates great difficulties, and therefore scientists began to build and operate linear electron accelerators, and also to look for a way of combating quantum fluctuations.

We note also that the relative energy can be strongly increased if the accelerators are constructed with counter (or colliding) beams.

It has already been mentioned that in the Frascati Laboratory (near Rome) the first storage devices for high-speed electrons and positrons with energies of 300 MeV have been built. There, there is a real possibility of setting up experiments on the scattering of electrons in colliding beams of electrons or positrons and to obtain an insight into their structure.

Construction of powerful accelerators will continue for about 5 to 10 years, and will require the mobilisation of many branches of the national economy and, in the first instance, will require the development of radio-electronics and technological improvement of computers, control and programming machines, which is foreseen in the grandiose programme of the Soviet Union and approved by the XXIInd Congress of the Communist Party of the Soviet Union.

At the Session of the Academy of Sciences, USSR, in February 1962, the question of the new principle of proton acceleration,

obtained by so-called autocorrection, was specially discussed. This principle was worked out by the Soviet scientists E. L. Burshtein, A. A. Vasil'yev, A. L. Mints, V. L. Petukhov and S. M. Rubchinskii.

It is well known that the greater is the energy of the accelerator, the greater is the distance which the particles must traverse in the process of acceleration. Thus, for example, in proton accelerators with strong focusing, a proton with an energy of around 30 GeV moving in a circular trajectory, covers a path equal to approximately the distance from the earth to the moon. As a result of this, in order that it be retained in the acceleration circuit the beam must not deviate from the calculated trajectory by more than 1 or 2 cm. If this is not the case, then it will escape from the acceleration circuit. In all modern accelerators, every possible deviation from trajectory should be taken into account beforehand, since after starting the accelerator, changes in the electromagnetic field take place independently of the motion of the beam. As a result of the new method of acceleration (autocorrection), local automatic regulation of the characteristics of the magnetic field is already provided for, according to information on the position of the beam, which can rectify occasional deviations. This method, according to accounts of Soviet authors, will enable a proton accelerator to be constructed (cybernetic accelerator) with energies of 300–1000 GeV.

If we construct not one, but two accelerators with these energies and if collision of these beams occurs, then the energy of one of the protons relative to the other proton may be increased to 10^{15} eV. This figure is for the present the theoretical limit, which in principle can be achieved today artificially for heavy particles under terrestrial conditions. In cosmic rays, particles have already been observed (in truth, only a few cases) with energies of 10^{19} eV. However, single cosmic particles with such a high energy are not enough to be used for investigating the elementary particles, since for this purpose it is essential to have an adequate beam intensity.

References for Further Reading

(These references range from the semi-popular to the sophisticated.)

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